# Multi-Site Air Sparging

**Battelle Memorial Institute**
**Columbus, Ohio**

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## List of Acronyms

| | |
|---|---|
| AFB | Air Force Base |
| ARAR | applicable or relevant and appropriate requirement |
| AS | air station |
| ASW | air sparging well |
| | |
| bgs | below ground surface |
| BTEX | benzene, toluene, ethylbenzene, and xylenes |
| | |
| CAH | chlorinated aliphatic hydrocarbon |
| CBC | Construction Battalion Center |
| cfm | cubic feet per minute |
| | |
| DCA | dichloroethane |
| DCE | dichloroethene |
| DNAPL | dense, non-aqueous phase liquid |
| DO | dissolved oxygen |
| DoD | Department of Defense |
| DoDHF | Department of Defense Housing Facility |
| DTW | depth to water |
| | |
| EPA | Environmental Protection Agency |
| | |
| GWMW | groundwater monitoring well |
| | |
| HASS | horizontal air sparging system |
| HDPE | high-density polyethylene |
| HP | horsepower |
| | |
| IAS | in situ air sparging |
| | |
| JP5 | jet propellant 5 |
| | |
| LF | landfill |
| LNAPL | light, non-aqueous phase liquid |
| | |
| MCAS | Marine Corps Air Station |
| MCB | Marine Corps Base |
| MCL | maximum contaminant level |
| MTBE | methyl *tert*-butyl ether |

| | |
|---|---|
| NAPL | non-aqueous phase liquid |
| NFESC | Naval Facilities Engineering Service Center |
| | |
| O&M | operation and maintenance |
| OMB | Office of Management and Budget |
| OU | operable unit |
| | |
| PCE | tetrachloroethene |
| POL | petroleum, oil, and lubricants |
| psi | pounds per square inch |
| PTW | pressure transducer well |
| PV | present value |
| PVC | polyvinyl chloride |
| | |
| RAO | remedial action objective |
| RBCA | risk based corrective action |
| RI/FS | remedial investigation/feasibility study |
| | |
| scfm | standard cubic feet per minute |
| SERDP | Strategic Environmental Research and Development Program |
| $SF_6$ | sulfur hexafluoride |
| SVE | soil vapor extraction |
| | |
| TCA | trichloroethane |
| TCE | trichloroethene |
| TPH | total petroleum hydrocarbons |
| TPH-G | total petroleum hydrocarbons as gasoline |
| TVH | total volatile hydrocarbon |
| | |
| UST | underground storage tank |
| | |
| VC | vinyl chloride |
| VMP | vapor monitoring point |

# Multi-Site Air Sparging


## Battelle Memorial Institute
## Columbus, Ohio


## 14 August 2002

## 1. Introduction

### 1.1 Background Information

The Department of Defense (DoD) is faced with the task of remediating many sites contaminated with a variety of compounds, including petroleum and chlorinated compounds. When a contaminant release occurs, the contaminants may be present in any or all of three phases in the geologic media: adsorbed to the soils, in free-phase form, and/or dissolved in groundwater. Of the three phases, dissolved contaminants in the groundwater are considered to be of greatest concern due to the risk of human exposure through drinking water. Conventional groundwater treatment technologies typically are expensive and often ineffective. In the past few years, the U.S. Air Force and Navy have been developing in situ remediation technologies that have the potential to remediate sites much less expensively and more effectively than conventional technologies. In particular, air sparging has been intensively studied by the Air Force in cooperation with the Navy at the Naval Base Ventura County (NBVC), Port Hueneme site, California, to evaluate proper monitoring techniques for evaluating system performance and to determine critical operating parameters.

Air sparging is the process of injecting clean air directly into an aquifer for remediation of contaminated groundwater. In situ air sparging remediates groundwater through a combination of volatilization and enhanced biodegradation. The induced air transport through the groundwater removes the more volatile and less-soluble contaminants by physical stripping. Increased biological activity is stimulated by increased oxygen availability.

Air sparging has been in general practice for a number of years (Ardito and Billings, 1990); however, the physics of the process were not well understood (Johnson et al., 1993) and, as a result, at numerous sites the technology failed to perform to expectations. One of the problems was that the process appeared to work, that is contaminant concentrations appeared to decline in monitoring

wells, but after site closure, contaminant concentrations increased or rebounded (Bass and Brown, 1996). In the same study, however, it was found that at some sites air sparging succeeded in remediating the groundwater and no rebound occurred. The result has been unpredictable results, and no good approach to evaluating a specific site, or developing a good site-specific design. The current state of the practice in the industry is a kind of trial-and-error approach, where contractors with substantial air sparging experience have better success than those without, largely as a result of the empirical experience they have gained. The U.S. Air Force, in coordination with the U.S. Navy, launched an effort two years ago to develop a new, rationally based design paradigm. The objectives were to develop a better understanding of the fundamentals of the process, to develop useful and cost-effective monitoring and pilot testing techniques, and to provide the DoD environmental engineering community with a manual to help improve design procedures, and reduce the trial-and-error nature of air sparging practice. The result has been the production of the Air Sparging Design Paradigm.

### 1.2 Official DoD Requirement Statement

Thirteen DoD needs have been identified as being applicable to this study and are identified as follows:

1. U.S. Air Force Need No. USAF 817 Technology to Remediate Trichloroethylene (TCE) and Other Chlorinated Organic Compounds in Soil and Groundwater

2. U.S. Air Force Need No. USAF 2008 Methods and Remedial Techniques are Needed to More Effectively Treat Groundwater Contaminated with Chlorinated Solvents Such as TCE, trichloroethane (TCA), and tetrachloroethene (PCE)

3. U.S. Air Force Need No. USAF 552 Develop a Method for In Situ Remediation of Soil and Groundwater Contaminated with TCE and Other Chlorinated Solvents

4. U.S. Air Force Need No. USAF 701 In Situ Treatment for Dense Nonaqueous-Phase Layers

5. U.S. Air Force Need No. USAF 574 Remediation of Groundwater Contaminated with Other Chlorinated Solvents

6. U.S. Air Force Need No. USAF 1611 Treatment of Chlorinated Hydrocarbons

7. U.S. Air Force Need No. USAF 242 Hazardous Waste Treatment Technologies for IRP Site Remediation of the Source of Chlorinated Organic Compounds

8. U.S. Air Force Need No. USAF 281 Hazardous Waste Treatment Technologies for IRP Site Remediation of the Plume of Chlorinated Organic Compounds

9. U.S. Army Need No. A(1.2.f) Alternatives to Pump and Treat

10. U.S. Army Need No. A(1.2.c) Solvents in Groundwater

11. U.S. Army Need No. 1.3e Innovative and In Situ Treatment Technologies for Organics (Non-Halogenated) in Groundwater

12. U.S. Army Need No. 1.I.1e Improved Remediation of Groundwater Contaminated with Non-Chlorinated Hydrocarbons

13. U.S. Navy Need No. 1.I.1e Improved Remediation of Groundwater Contaminated with Chlorinated Hydrocarbons and Other Organics

Except for Item 9, the needs listed above all relate to the need to develop in situ technologies that are capable of remediating chlorinated solvents and other contaminants in groundwater. Although previous work in air sparging has focused on petroleum hydrocarbon contamination, air sparging is applicable to chlorinated solvent contamination as well, and both were investigated as part of this current study. Item 9 refers to development of alternative technologies to pump and treat. To date, air sparging is one of the most promising technologies as a replacement to pump and treat, particularly if it is designed carefully. This study focused on development of better guidelines for the evaluation and design of air sparging systems, thereby meeting the needs listed above.

### 1.3 Objectives of the Demonstration

The objective of this demonstration is to evaluate and implement the Air Sparging Design Paradigm, developed during previous air sparging work at the Naval CBC, Port Hueneme, CA. This Air Sparging Design Paradigm will be evaluated at several sites across the DoD to test its validity at sites with varying geology and contaminant distribution. In addition, the demonstration will serve to disseminate new information about air sparging to Base environmental mangers to assist with task of evaluating remedial proposals for contaminants.

## 1.4 Regulatory Issues

In general, regulatory issues are of most concern when soil vapor extraction is necessary in conjunction with air sparging. Soil vapor extraction introduces a point source into the process, which must be properly treated and permitted. Small amounts of groundwater are removed for sampling and these also must be treated.

# 2. Technology Description

## 2.1 Description

Air sparging is a process where air is injected directly into the saturated subsurface to (1) volatilize contaminants from the liquid phase to the vapor phase for treatment and/or removal in the vadose zone, and (2) biodegrade contaminants in the saturated zone via stimulation by the introduction of oxygen. Which mechanism accounts for the greater amount of contaminant removal depends on the chemical properties, contaminant distribution, duration of air injection, and soil properties. Generally, volatilization dominates when systems are first turned on and, for aerobically degradable compounds, biodegradation will dominate in later phases of treatment. Volatilized contaminants may be biodegraded in the vadose zone, or may be extracted and treated or discharged, depending on regulatory requirements.

The term biosparging is frequently used to refer to certain types of air sparging systems. There is no clear cut difference between biosparging and air sparging; however, when the term biosparging is used, it usually means that the intent of the operator is to stimulate biodegradation rather than volatilization, typically by using lower air injection rates. For heavier-molecular-weight, non-volatile contaminants, biosparging may be the only approach possible. In addition, many practitioners use the term biosparging to refer to systems that lack soil vapor extraction for vapor collection, since the object is to stimulate biodegradation either in the saturated zone or the unsaturated zone, but before vapor emission.

Practitioners have proposed using in situ air sparging to (1) treat contaminant source areas trapped within water-saturated and capillary zones, (2) remediate dissolved contaminant plumes, or (3) provide barriers to prevent dissolved contaminant plume migration. Most practitioners advocate targeting the source zone for remediation of petroleum-contaminated aquifers, and air sparging is one of the most effective submerged source zone treatment technologies. In the case of most petroleum hydrocarbons, if the source zone can be remediated, then the remaining dissolved plume rapidly dissipates due to natural processes. There may be occasions, however, when plume remediation is warranted. This might be the case when one needs to prevent against further migration of a recalcitrant chemical like TCE or methyl *tert*-butyl ether (MTBE).

The use of air sparging has increased rapidly since the early 1990's. Based on informal surveys of underground storage tank (UST) regulators, it is now likely to be the most practiced engineered in situ remediation option when targeting the treatment of hydrocarbon-impacted aquifers. The feasibility assessment, pilot testing, design, and operation of air sparging systems has remained largely empirical, with variability in approaches by different practitioners (Bruell et al., 1997;

Johnson et al., 1993; Johnson et al., 1997; U.S. Environmental Protection Agency [EPA], 1992). Since the mid-1990's, much research has been devoted to gaining a better understanding of air sparging systems; however, as discussed in P.C. Johnson et al. (2001), it appears that valuable knowledge gained from these studies has yet to be integrated into practice, and many of the current approaches to feasibility assessment, pilot testing, design, and operation show a lack of appreciation for the complexity of the phenomena and the sensitivity of the technology to design and operating conditions.

In the mid-1990's, the U.S. Air Force Research Laboratory, Airbase and Environmental Technology Division, Tyndall Air Force Base (AFB) initiated an air sparging project funded by the Airbase and Environmental Technology Division (AFRL/MLQE), the Strategic Environmental Research and Development Program (SERDP), and the U.S. Naval Facilities Engineering Service Center (NFESC). This project was conducted by the authors of this document, with input and review from an expert panel comprised of practitioners, program managers, and members of academia. Under this project, both laboratory- and field-scale experiments were conducted, and the results of the individual studies have been, and continue to be reported elsewhere (Amerson, 1997; Amerson et al., 2001; Bruce et al., 1998; 2001; Johnson et al., 1999; Rutherford and Johnson, 1996). The ultimate goal of this project, however, has been the development of a technically defensible and practicable air sparging Design Paradigm.

## 2.2 Process Description

A typical air sparging system is shown in Figure 2-1. The major components of a typical air sparging system are shown, including an air injection well, an air compressor or blower to supply air, monitoring points and wells, and an optional vapor extraction system.

The air injection wells generally are vertical and are screened at depths located below the contamination level. The wells are grouted to depths below the water table to prevent short-circuiting of air through a sand pack into the vadose zone (Figure 2-2). If the medium is homogenous sand (Figure 2-3a), the airflow will be relatively uniform around the air injection well, resulting in good mass transfer. In contrast, a heterogeneous medium may result in non-uniform and confining airflow thus reducing air sparging effectiveness (Figure 2-3b). In practice, all sites have some degree of soil heterogeneity and nonuniform air flow is common. The practitioner must ensure that the nonuniformity of air flow is acknowledged and accounted for in system design. In situations where the contaminated subsurface is under buildings, runways, or other structures through which well installation is impossible, horizontal or inclined air injection wells may have to be considered.

Compressors or blowers are needed to supply air to the injection wells. The selection of a compressor or blower depends upon site-specific characteristics that dictate air flow and pressure requirements.

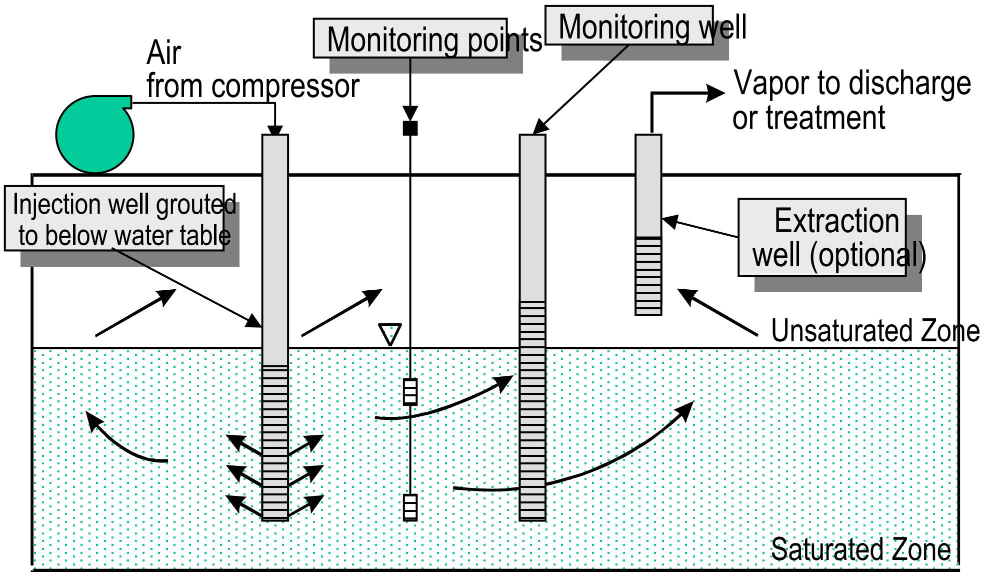



**Figure 2-1. Schematic Diagram of a Typical Air Sparging System**

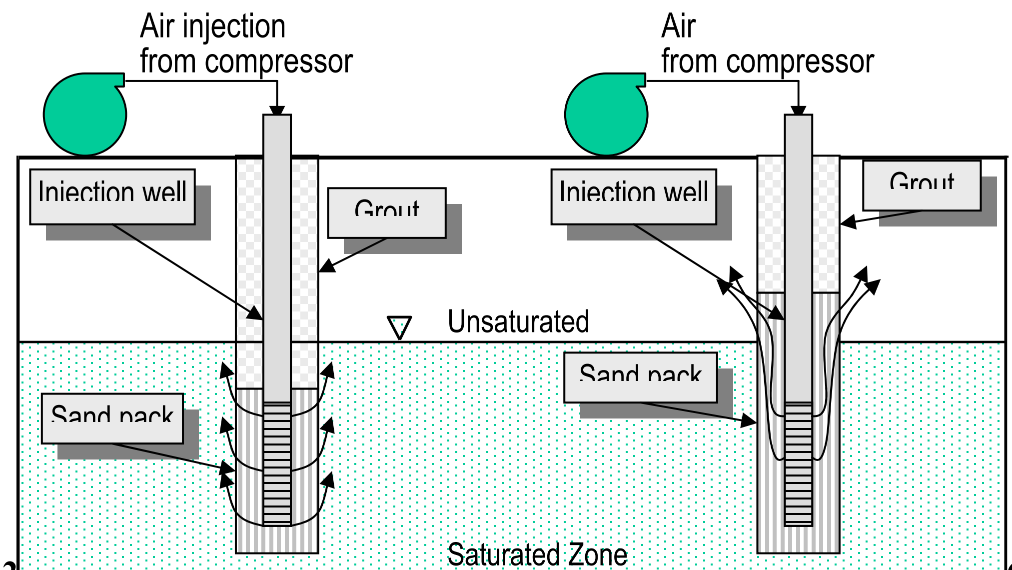
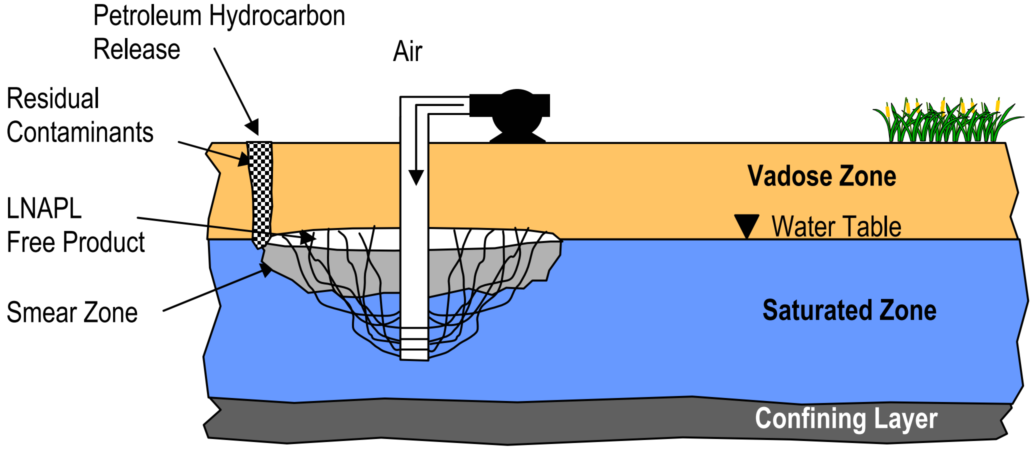



**Figure 2-2. Construction Details and Air Flow Patterns of an Air Sparging Well Grouted Below and Above the Water Table**

A)




B)

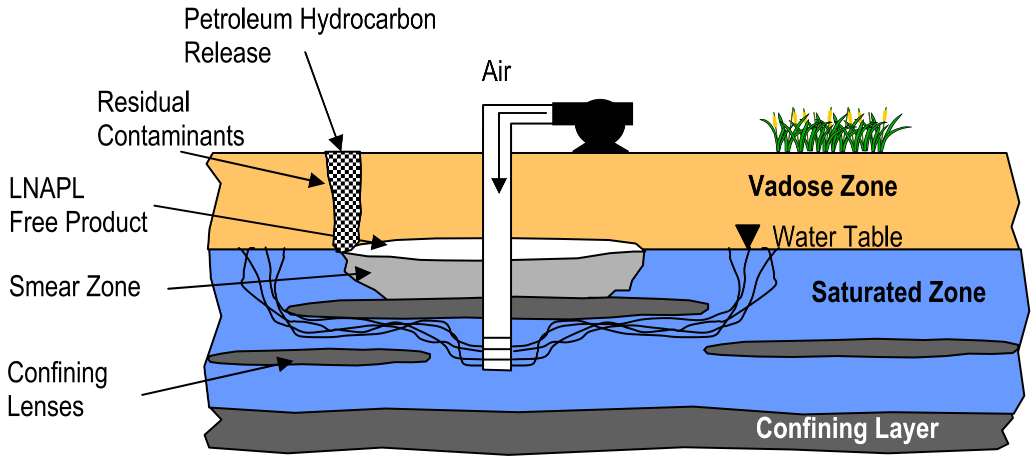



**Figure 2-3. Air Flow Patterns When Sparging in a (A) Homogeneous or (B) Heterogeneous Soil Structure**

The monitoring points and related equipment are needed to provide information on compressor air flowrates and pressure, and contaminant concentrations in the groundwater, soil, and effluent air stream to analyze the progress of the remediation. In some air sparging systems, an optional vapor extraction well is installed to transfer contaminated vapor from the vadose zone for treatment and or emission to the atmosphere.

Unique design criteria for the air sparging technology as prescribed by the Air Sparging Design Paradigm are evident during pilot testing, system design, and system monitoring as follows:

- Pilot testing
  - Determine affordable well spacing based on site budget
  - Evaluate air distribution
  - Look for problems with air distribution

- System design
  - Select well spacing: standard or site-specific approach
  - Determine air flow system

- System monitoring
  - Use of discrete groundwater sampling points

The air sparging pilot test has been significantly streamlined to evaluate a small number of key parameters that would indicate whether air sparging is feasible. This differs from the traditional approach where pilot testing was used to attempt to determine design parameters for scale-up. Research demonstrated that a short-term pilot test is not sufficient to provide a good indicator of the long-term performance of an air sparging system; however, it can provide information on whether there are difficulties with air distribution and therefore with successful air sparging.

The system design itself then also has been streamlined, recognizing the fact that air distribution can be problematic and difficult to delineate with any degree of confidence. The practitioner is advised therefore, to use a small well spacing to provide the maximum air to contaminant contact. This has been termed the Standard Design Approach where a 15-ft well spacing is implemented. The Site-Specific Design Approach is for practitioners with large sites who need to reduce costs associated with well installation. At these sites, more careful evaluation of air distribution is recommended to ensure larger well spacings are feasible. Also as part of the system design, pulsed operation of banks of two to five injection wells for four reasons: a) the difficulty of controlling a multi-well air injection system increases as the number of wells manifolded together increases, b) the required system injection flow capacity is lower in this mode, c) studies suggest that performance can be improved by operating in a pulsed mode, and d) pulsed operation may be necessary in air sparging barrier applications to prevent groundwater bypassing due to water relative permeability reductions caused by air injection (P.C. Johnson et al., 2001).

System monitoring is accomplished from monitoring individual rotameters on each air injection well, and using discrete level groundwater monitoring points to measure groundwater contamination. Soil gas monitoring points can also be used for contaminant measurements in addition to tracer measurements.

Air sparging has been demonstrated to be very effective at contaminant reduction, both for petroleum hydrocarbons and chlorinated solvents. A combination of volatilization and biodegradation allow for removal of many compounds to below detection limits. Historically, many sites have shown significant rebound of contaminant concentrations after conducting air sparging. The cause of this appears to be primarily due to poor monitoring techniques that indicated the site was clean. Improved monitoring techniques such as the discrete sampling from groundwater monitoring points should alleviate this problem; however, it is recommended that sites continue to be sampled for at least one year after discontinuing air sparging.

Personnel and training requirements for the air sparging technology are relatively simple. A field technician capable of performing weekly system checks to verify air flowrates and proper operation of the system compressor is sufficient. Compressors will require periodic maintenance, but can generally operate for several years before replacement is necessary. Maintenance of compressors is specific to the compressor and guidance should be sought from the manufacturer. Health and safety requirements also are minimal, unless subsurface structures or buildings are within the zone of influence of the air sparging system. In these situations, care must be taken that vapors are not pushed into these structures, potentially causing explosive or toxic environments.

## 2.4 Advantages and Limitations of the Technology

While air sparging has a number of advantages over competing technologies, the technology is not without limitations. Listed below are a number of advantages and limitations of air sparging.

***Advantages of Air Sparging***

- Since only readily available commercial equipment is utilized (i.e. polyvinyl chloride (PVC) well casing, compressors or blowers, etc.), air sparging is a simple and low cost technology to implement. The equipment is easy to install and causes minimal disturbance to site operations.

- Once the system is installed at a site, it requires minimal operational oversight relative to soil vapor extraction (SVE) systems, which demand extensive monitoring.

- There are no waste streams generated that require treatment because the exiting air stream can be vented directly to the atmosphere.

- At sites where smear zone contamination has developed due to a fluctuating water table, air sparging is effective at treating the smear zone since air moves vertically upward through this region.

- The technology is effective in treating source area contamination, thereby limiting off-site migration of dissolved contaminants.

- The technology is compatible with other remediation technologies such as SVE and bioventing.

- Because biodegradation is a component of the air sparging process, this technology has the potential to mineralize contaminants rather than simply transferring contaminants to another medium.

***Limitations of Air Sparging***

- The technology is not suitable for treating contaminants with low values of Henry's Law constants or low volatility unless the compound is aerobically biodegradable. Semi-volatile contaminants with low aerobic biodegradability are not treated effectively with air sparging.

- Sites that contain contaminants that can be removed effectively via biodegradation, but not volatilization, were remediated slowly due to relatively slow biodegradation rates.

- Site geological conditions such as stratification, heterogeneity, and anisotropy, will prevent uniform air flow through the medium to reduce air sparging effectiveness.

- Free product (nonaqueous phase liquid [NAPL]) in large quantities may come in limited contact with the injected air. This may be a particular concern with dense nonaqueous phase liquids (DNAPLs) that will sink to the bottom of the aquifer, thereby limiting the effectiveness of air sparging.

- There is a potential for migration of volatilized contaminants into buildings and other structures (accounting for vapor migration in system design can often alleviate this problem).

- When air sparging is applied to contain a dissolved phase plume, a zone of reduced hydraulic conductivity could form and, if not managed properly, could allow the plume to circumvent the zone of air sparging influence.

- Air flow is effective over a defined area, possibly requiring a large number of wells to obtain adequate air flow through the contaminated region.

### 2.5 Factors Influencing Cost and Performance

The key factors that impact air sparging project costs are:

- Area of groundwater contamination
- Depth to groundwater
- Depth to base of groundwater contamination
- In situ heterogeneity
- Treatment period

As can be seen from this list of parameters, the factors that impact project costs are therefore very site-specific. Parameters such as the area of groundwater contamination, depth to groundwater, and depth to the base of groundwater contamination are fixed once site characterization is completed, and typically will not change significantly once the air sparging system is installed.

In contrast, the in situ heterogeneity can impact project costs and cause them to differ from original predictions once air sparging is initiated. While pilot testing is useful to evaluate portions of the site, the practitioner must be aware that in situ heterogeneities will exist throughout the site and could impact air distribution to the point that additional system engineering may be required after installation to ensure that the target treatment zone is adequately treated. The Standard Design Approach was developed to avoid this problem, by prescribing close well spacings to provide the maximum possibility of success.

The total treatment period also is difficult to predict in advance. If an air sparging system must be operated for longer than predicted, the cost of additional monitoring for a 2-year period can be significant, particularly if air extraction and treatment must be conducted during this time. The practitioner can make reasonable estimates based on past performance; however, this is an uncertainty in project costs.

# 3. Site/Facility Description

## 3.1 Background

Ten field sites were selected for study. The criteria used to select the test sites were as follows:

- Various soil types (i.e. site with sandy soils compared to sites with predominantly clayey soils)

- Various contaminants (i.e. petroleum hydrocarbons or chlorinated solvents)

- Willingness of Base personnel to allow testing at their site

- Air sparging equipment in place:
  - Air delivery system
  - Vapor extraction system
  - Sparge wells
  - Groundwater monitoring wells

- Proper design of the equipment
  - Sparge well screen interval starts below 5 ft, but no more than 10 ft under the groundwater table
  - Sparge wells grouted beneath the groundwater table
  - Soil vapor extraction well capable of capturing 80% of the injection air
  - Air compressor or blower capable of delivering 5 to 20 cubic feet per minute (cfm) into the sparge well.

## 3.2 Site/Facility Characteristics

Ten test sites were selected for testing and/or evaluation. Table 3-1 lists the site characteristics including site name, former role of the site, type of air sparging system installed, soil type, depth to groundwater, and contaminant type and concentration. Additional detail on all sites except Port Hueneme is provided in the following sections. Details on Port Hueneme are provided in a separate document as an attachment to the Air Sparging Design Paradigm (Appendix D).

**Table 3-1. Site Characteristics**

| Installation | Site Name | Site History | Type of System | Soil Type | Depth to Groundwater | Contaminant Type | Contaminant Concentration |
|---|---|---|---|---|---|---|---|
| Eielson AFB, AK | ST10/SS14 | POL yard & landfill | Bioventing; can inject below water table | Sandy loam soil; sand & gravel below | 8 ft | BTEX, anthracene, & naphthalene in groundwater | Benzene up to 460 µg/L in groundwater |
| NBVC, Port Hueneme site, CA | NEX Gasoline Station | Gasoline Station | Full-scale sparging, based on ASDP | Fine to coarse sand | 8 ft | BTEX & MTBE | Benzene (39 mg/L) & MTBE (10 mg/L) |
| Cape Canaveral AS, FL | FT-17 (CCFTA-2) | Firefighter Training Area | Horizontal well | Sand | 6 ft | Vinyl chloride | VC up to 4,000 µg/L in groundwater |
| Fort Lewis, WA | LF4 | Landfill | Air sparge/SVE curtain | Outwash sands & gravels, glacial till | 30-35 ft | TCE, DCE, & VC in groundwater | TCE (150 µg/L), DCE (12 µg/L), VC (7.8 µg/L) |
| Fairchild AFB, WA | FT-1 | Firefighter Training Area | Air sparging curtain | Silty sands & gravels | 3-7 ft | BTEX, CAHs in groundwater | Total BTEX up to 1,320 µg/L in groundwater |
| Marine Corps Base Camp Lejeune, NC | LCH-4015 | Gasoline station, fuel farm | Full-scale air sparging system | Fine sand to sandy clay | 3-5 ft | Benzene, ethylbenzene, xylenes, MTBE | Benzene (10,600 µg/L), ethylbenzene (2,960 µg/L), total xylenes (9,960 µg/L), MTBE (256 µg/L) |
| Marine Corps Base Camp Pendleton, CA | MCAS Fuel Farm | Air Station Fuel Farm | Full-scale sparging, based on ASDP | Sand & silty sand | 4-15 ft | TPH, BTEX | TPH up to 27 mg/L |
| DoD Housing Facility Novato, CA | Site 957/970 | PWC service station USTs | Hot spot removal by sparging & SVE | Sand, gravel, & clay | 3-13 ft | TPH, BTEX, MTBE | TPH (>100,000 µg/L), Benzene (>1,000 µg/L), MTBE (>30,000 µg/L) |
| McClellan AFB, CA | OU A | Industrial degreasing facility | CAS pilot demonstration | Sand & gravel aquifer | 110 ft | PCE & daughter products, DCA | TCE (>1,000 µg/L), DCE (88 µg/L) |
| Hill AFB, UT | OU-6 | UST | Pilot study | Sands & silty sands | 100 ft | TCE | 440 µg/L |

AS = Air Station; ASDP = Air Sparging Design Paradigm; BTEX = benzene, toluene, ethylbenzene, and total xylenes; CAH = chlorinated aliphatic hydrocarbon; CAS = cometabolic air sparging; DCE = dichloroethene; NEX = Naval Exchange; NVBC = Naval Base Ventura County; PCE = tetrachloroethene; POL = petroleum, oil and lubricants; TPH = total petroleum hydrocarbon; VC = vinyl chloride

**3.2.1 Site ST10, Eielson AFB, AK.** Eielson AFB is an active Air Force Base located in the Alaskan Interior region approximately 25 miles southeast of Fairbanks, Alaska. The base serves a large variety of aircraft and maintains a relatively high volume of traffic. The climate is characterized as subarctic with low annual precipitation and an average annual temperature near 0°C (32°F). Temperatures in the region cover a broad range, with winter lows falling below -30°C (-22°F) and summer highs exceeding +30°C (86°F).

The base topography is predominated by the Tanana-Kuskokwim Lowland. Soils consist primarily of glaciofluvial deposits derived from glacial outwash from the Alaskan Mountain Range. The general lithology consists of a thin layer of sandy loam overlying a 200- to 300-ft-thick sequence of sand and gravel (Harding Lawson Associates, 1989). Permafrost is present in some areas on the base. Groundwater on the base typically is encountered at 5 to 15 ft. The aquifer underlying the base is characterized as a sole-source aquifer with generally good groundwater quality, but with a few contaminated areas (Harding Lawson Associates, 1989).

Site ST10 consists of the E-2 Petroleum, Oil and Lubricants (POL) Yard and Hardfill Lake (Figure 3-1). The E-2 POL storage area consists of a tank farm with six 16,000-barrel aboveground storage tanks that are currently in use for storage of JP-4 jet fuel and aviation gasoline. Hardfill Lake is an old gravel pit lake where the land surrounding the lake was used as a permitted landfill for the disposal of demolition debris. Site SS14 is located a few hundred feet south of the tank farm parallel to the railroad tracks, but is considered as one site for the remedial system. Depth to groundwater at Site ST10/SS14 is approximately 8 ft below ground surface (bgs).

Leaks and spills from the aboveground tanks and associated piping have caused soil and groundwater contamination in the area. Benzene, toluene, ethylbenzene, and total xylenes (BTEX) as well as anthracene and naphthalene have been detected in groundwater. Benzene concentrations above the site-specific remedial action objectives (RAOs) and applicable or relevant and appropriate requirements (ARAR) maximum contaminant limits (MCLs) have been detected in monitoring wells 10-3 (150 µg/L), 14-2 (460 µg/L), and W-1 (71 µg/L). The locations of the monitoring wells are shown in Figure 3-2.

The existing injection wells are screened from approximately 14 to 19 ft bgs. A total of 18 air injection wells and 13 soil gas monitoring points have been installed at the site.

**3.2.2 Site FT-01, Fairchild AFB, WA.** Fairchild AFB is located in eastern Washington, approximately 12 miles west of the city of Spokane. The Base occupies about 4,300 acres and contains aircraft operational facilities, a survival school, weapons storage, and base personnel housing and support facilities. The base was established in 1942 as an Army repair depot, and was transferred to the Strategic Air Command in 1947. The base is currently under the Air Mobility Command, and serves as the home of the 92$^{nd}$ Air Refueling Wing and the Washington Air National Guard 141$^{st}$ Air Refueling Wing.

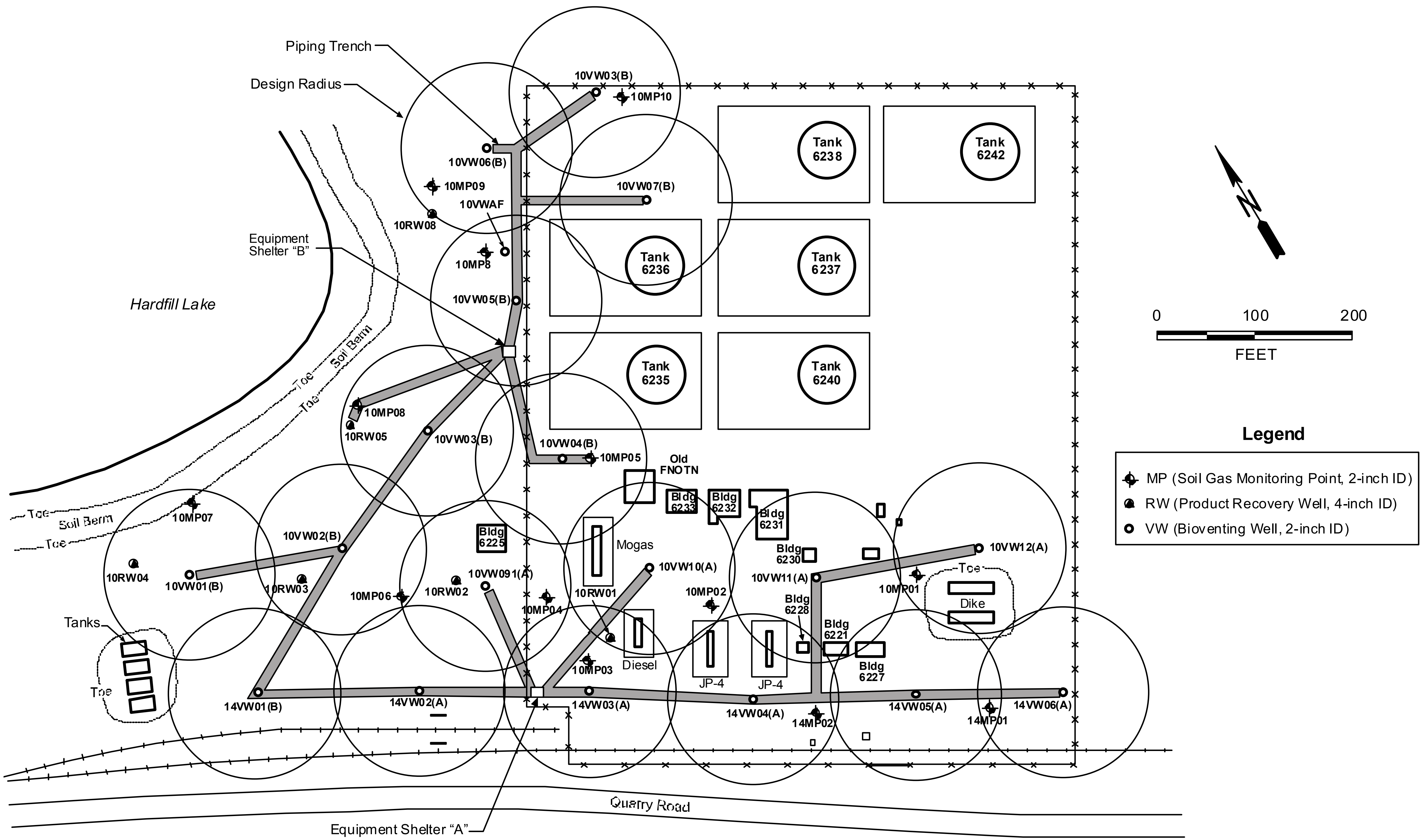



**Figure 3-1. Schematic Diagram of ST10 Showing Well Locations, Eielson AFB**

Fairchild AFB is situated on the Columbia Plateau, which is surrounded by mountain ranges on all sides. The topography of the base and its vicinity is flat to gently rolling grasslands, at an elevation of approximately 2,400 ft above mean sea level. Surface water in the area of Fairchild AFB drains to the Spokane River. Surface water on the base is nonexistent or intermittent, due to precipitation runoff (Parsons Engineering Science, 1997).

Site FT-01 is a former fire training area located near the eastern boundary of Fairchild AFB, between Taxiway 10 and Perimeter Rd. Fire training exercises were conducted at the site from the early 1960s to 1991. During training exercises, JP-4, waste oils, and solvents were burned in an unlined fire training pit. Fuel was contained on site in an underground storage tank. A map of Site FT-01 is shown in Figure 3-2. After the exercises, water, unburned fuel, and aqueous film-forming foam (extinguishing agent) were drained from the pit into an oil/water separator. The separator discharged to a low area east of the pit. Dead vegetation and fuel stains observed in the discharge area during a 1991 Remedial Investigation indicated that unburned fuels were discharged by the oil/water separator (Dames and Moore, 1998).

A sequence of unconsolidated sediments approximately 9 to 30 ft thick overlies the basalt bedrock at FT-01 (Figure 3-3). Shallow deposits are silty clays and clayey silts, while deeper sediments are coarser, with silty sands and gravels. Shallow groundwater occurs in the unconsolidated sediments and the upper basalt bedrock, with the water table at approximately 5 to 7 ft bgs at the site.

Soil contamination has been detected near the fire training pit and the outfall of the oil/water separator. Groundwater samples collected near the fire training pit were contaminated by BTEX, as well as low concentrations (<5 µg/L) of chlorinated aliphatic hydrocarbons (CAHs). Total BTEX concentrations up to 1,320 µg/L have been detected. CAHs were detected underlying the site and up to 5,500 ft downgradient. Neither light non-aqueous phase liquids (LNAPLs) nor DNAPLs have been detected at FT-01 (Parsons Engineering Science, 1997).

An air sparge curtain, Air Sparge West, was installed at the FT-01 site in the center of the contaminant plume. The curtain crosses the plume perpendicular to the direction of groundwater flow (Figure 3-4). Four vapor monitoring points (VMPs) are installed at the site to monitor oxygen, carbon dioxide, and total volatile hydrocarbons (TVH) in the soil gas.

The sparge curtain consists of 19 sparge wells each screened from 8.5 to 10.5 ft bgs. The wells are constructed of 1.25-inch-diameter galvanized steel, with 0.10 inch slotted stainless steel screens. Underground piping to the sparge wells consists of 1-inch-diameter high-density polyethylene (HDPE). The VMPs are constructed of ¼-inch-diameter schedule 80 PVC tubing from the surface to 2.5 ft bgs, where it connects to a 6-inch-long section of 1-inch-diameter, 0.02-inch slotted screen (R&R, 1998).

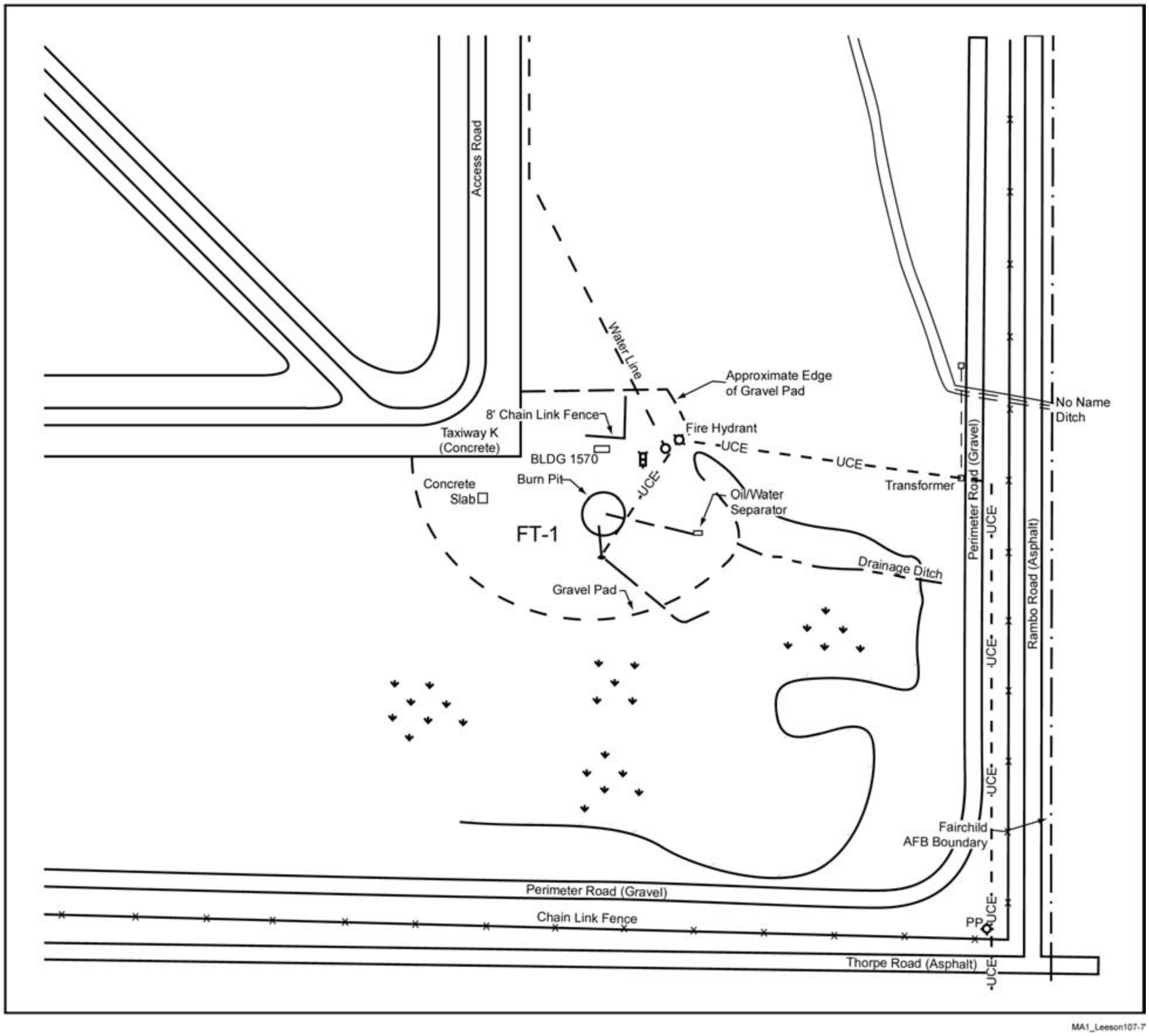



**Figure 3-2. Schematic Diagram of Site FT-1, Fairchild AFB, WA**

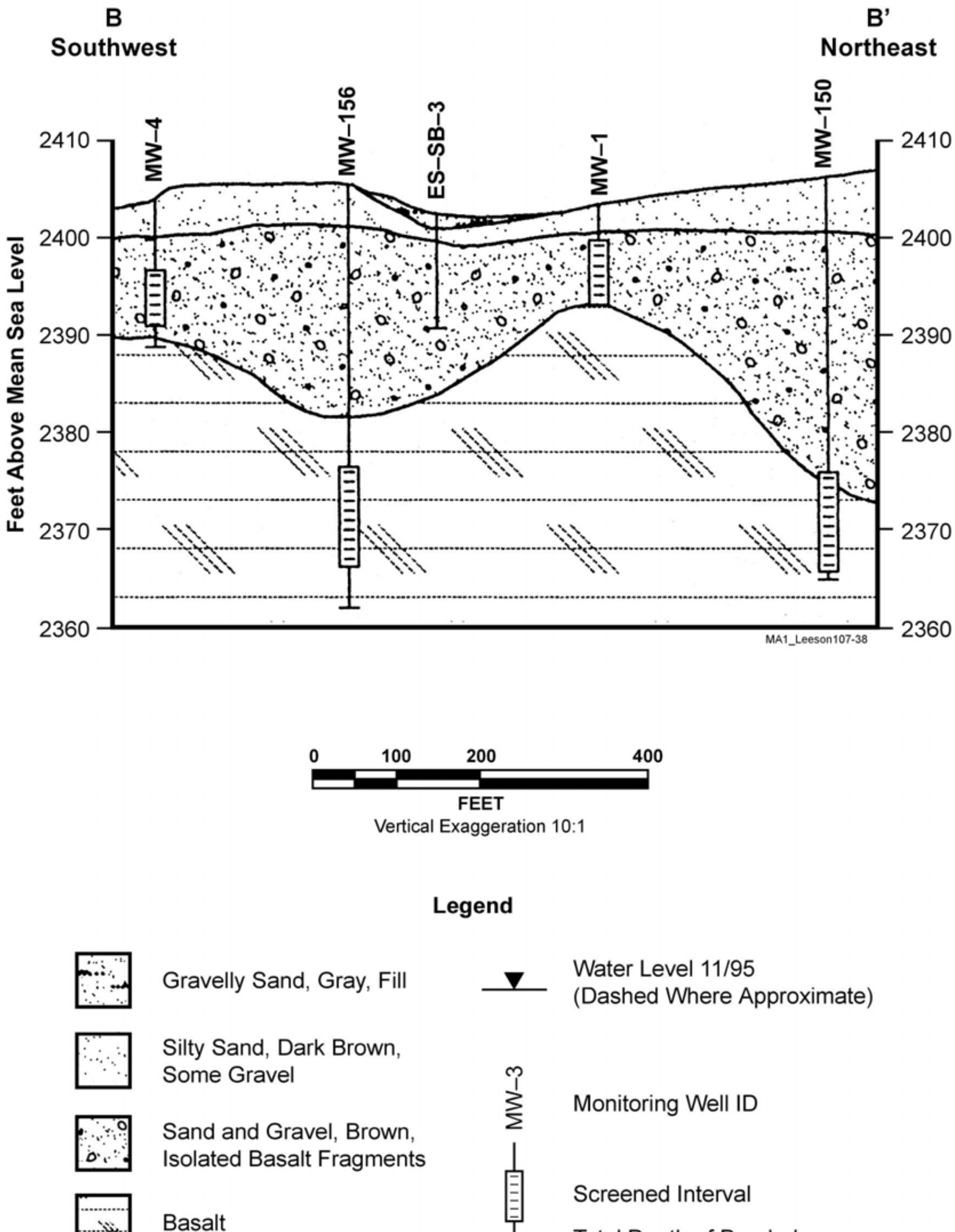



**Figure 3-3. Cross-Section of Site FT-1 Illustrating Site Geology, Fairchild AFB, WA**

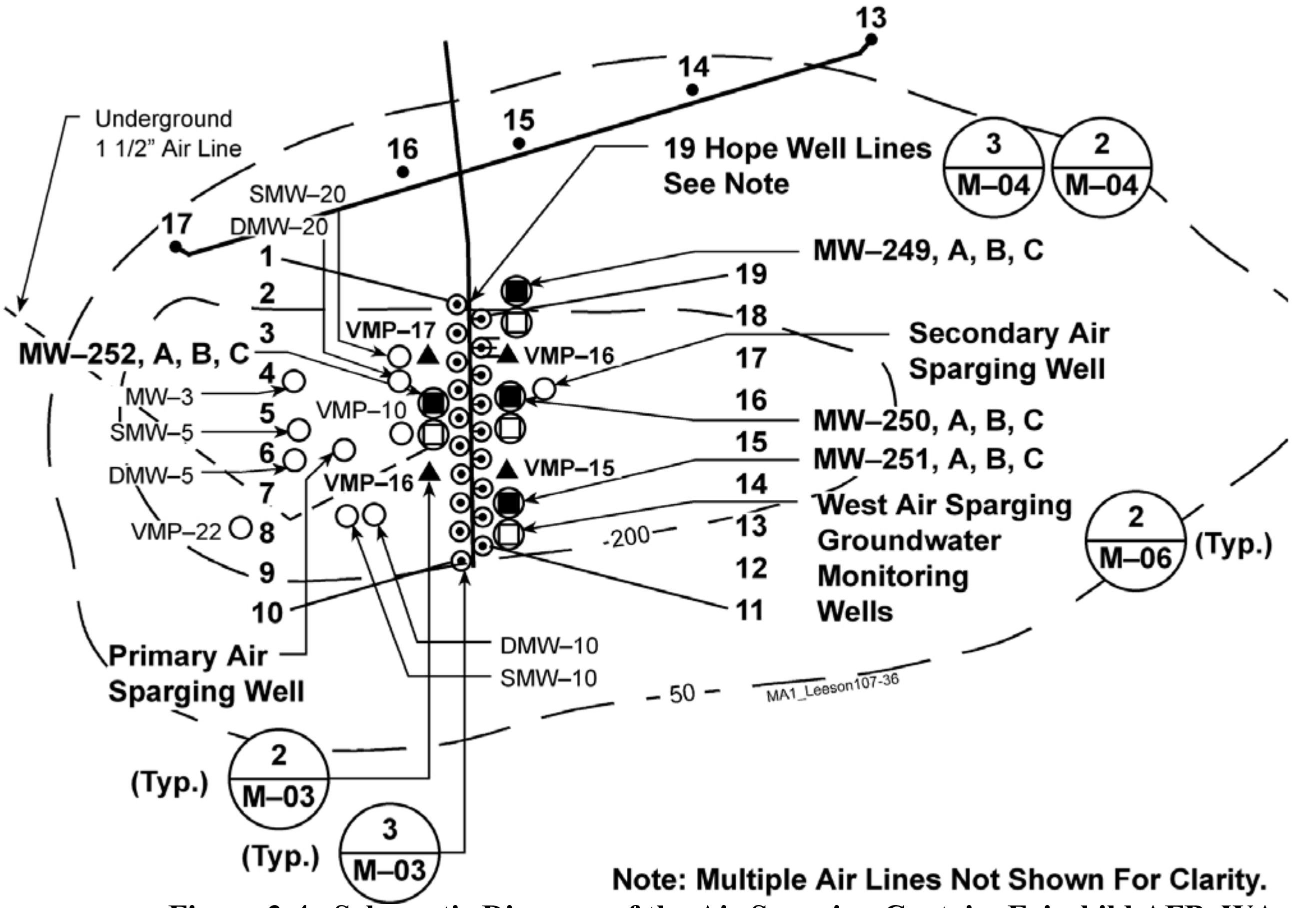



**Figure 3-4. Schematic Diagram of the Air Sparging Curtain, Fairchild AFB, WA**

The Air Sparge West system consists of a 10 horsepower (HP) rotary lobe positive displacement blower (Roots Model 36 URAI), supplying up to 12 standard cubic feet per minute (scfm) at 5 pounds per square inch (psi) to each of the 19 air injection wells. The outlet of the blower is fitted with a pressure relief valve. The blower inlet is fitted with a filter, silencer, vacuum gauge, and vacuum relief valve. The blower, associated electrical equipment, and process controls are housed within a 10 × 28-ft equipment building.

Monitoring equipment for the system includes sampling points for flow at each sparge well and four locations in the manifold system. Pressure gauges at the inlet and outlet of the blower and at each sparge well. In addition, conventional groundwater monitoring wells have been installed upgradient and downgradient of the air sparge curtain. The monitoring wells are designed to evaluate contaminant concentrations in the groundwater at the site.

**3.2.3 Landfill 4, Fort Lewis, WA.** Fort Lewis is an active Army post located in west-central Washington state, approximately half-way between the cities of Tacoma and Olympia. Fort Lewis is divided by Interstate 5 into North Fort Lewis and the Main Post. The post sits in the Puget Sound

Lowland, which is bounded on the west by the Olympic Mountains and on the east by the Cascade Mountains (Garry Struthers Associates, 1996).

Landfill 4 (LF4) comprises approximately 52 acres on North Fort Lewis, and is divided into three cells. LF4 was used as a gravel source dating back to the early 1940s, and served as a waste disposal site from the early 1950s until 1970. No tipping records are available, but it is believed that the site was used for domestic and light industrial waste disposal. Aerial photographs of the site also indicate two possible liquid waste disposal pits in the Northeast and South cells.

The topography at LF4 is flat to hummocky, with elevations ranging between 210 and 250 ft above sea level. The thickness of the refuse ranges between approximately 9 to 20 ft. After completion of landfill activities, the site was covered with compacted native soil. The land surface is covered in some places by grasses and scattered trees. However, landfill debris is exposed in some portions of LF4 where the surface cover is thin or not present (Garry Struthers Associates, 1996).

Fort Lewis is underlain by a thick sequence of unconsolidated sediments of glacial and non-glacial origin. The uppermost unit of these sediments, the Vashon Drift, is the only unit penetrated by the air sparging/SVE system at LF4. The Vashon Drift is composed of several sub-units, including outwash sands and gravels and glacial till.

Water level data has been collected since 1996 in wells completed in the upper aquifer (the Vashon Drift). Water table elevations for these wells have consistently been between 211 and 214 ft above sea level (Garry Struthers Associates, 1998). Well completion diagrams for the sparge wells installed at LF4 indicate a static water level of approximately 30 ft bgs.

Operation of the landfill and gravel quarrying activities at LF4 have caused soil and groundwater contamination in the area. Contamination in the upper aquifer consists primarily of TCE and its daughter products, dichloroethene (DCE) and vinyl chloride (VC). TCE concentrations as high as 150 ppb have been observed in samples from well LF4-MW8A. DCE has also been detected in LF4-MW8A, with concentrations up to 12 μg/L. VC concentrations up to 7.8 μg/L have been observed in well MW-15B. A site map showing the locations of the monitoring wells is shown in Figure 3-5.

The remedial system currently in place at LF4 is an air sparging/soil vapor extraction system located just south of the Northeast landfill cell. The air sparging system includes five injection wells in an east-west line on 50-ft spacings. Each sparge well was drilled to a total depth of 50 ft bgs, with 2-inch diameter, 0.010-slot screen from 45 to 50 ft bgs. The system is designed to operate at a pressure of 8 psi with a total maximum flow of 130 cfm at each wellhead (650 cfm total). The SVE system includes six SVE wells, installed in two parallel rows of three on either side of the row of injection

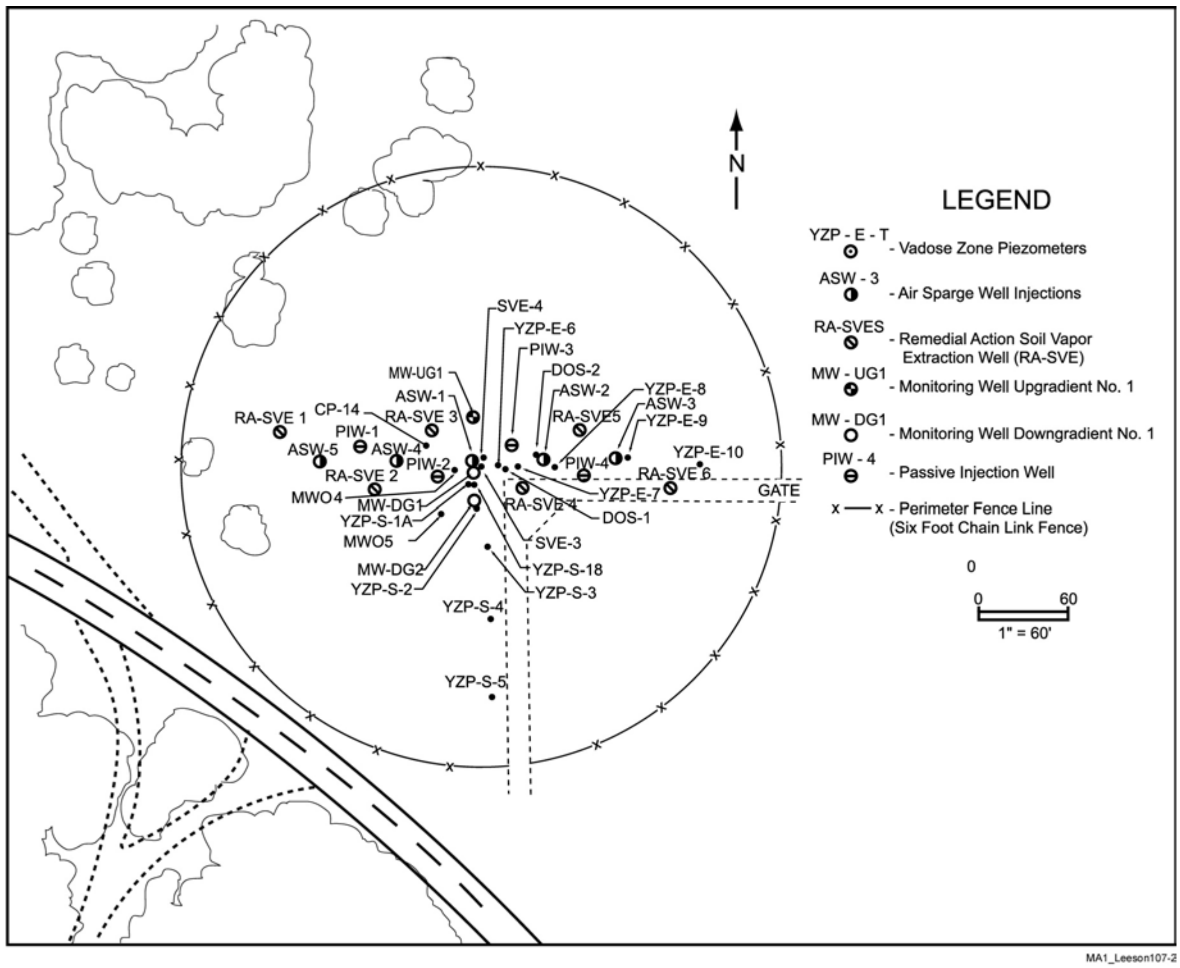



**Figure 3-5. Schematic Diagram of the Air Sparging System at Landfill 4, Fort Lewis, WA**

wells. The two rows of SVE wells are 40 ft apart, and the wells in each row are separated by 40 ft. Each SVE well was drilled to a total depth of 30 ft bgs, with 4-inch diameter, 0.010-slot screen from 18 to 28 ft bgs. The SVE system is designed for a maximum flow of 200 cfm per well (1,200 cfm total), with 6″ Hg vacuum at the blower inlet. Several other wells exist in the vicinity of the air sparging/SVE system, including one upgradient and two downgradient monitoring wells, four passive injection wells, and 11 vadose zone piezometers.

**3.2.4 Cape Canaveral Air Station (AS), FL.** Cape Canaveral AS is located on the east coast of Florida, on a barrier island in Brevard County. The main complex occupies about 25 square miles of assembly and launch facilities for missiles and space vehicles. The property is bounded by the Atlantic Ocean to the east and the Banana River to the west. Since 1950, Cape Canaveral has been a

proving ground for the country's military missile program, including the Bomarc, Matador, Redstone, Atlas, Titan, and the Navy Trident programs (Parsons Engineering Science, Inc., 1997).

Site FT-17 (CCFTA-2), located approximately 1,000 ft from the Banana River, is a former fire training area located at Cape Canaveral AS. Fire training exercises were conducted at the site between 1965 and 1985. During training exercises, waste fuels and waste oils (including halogenated and non-halogenated solvents) were burned in an unlined fire training pit. Fuel was contained on site in aboveground storage tanks and distributed to the burn pit via aboveground pipelines. The tanks and associated piping subsequently were removed from the site. Because of the presence of sandy soils and the lack of a liner system in the fire training pit, the infiltration of fuels and petroleum products likely occurred before the wastes were ignited (Parsons Engineering Science, Inc., 1997).

During the Remedial Investigation/Feasibility Study (RI/FS) activities performed at Site FT-17 in 1989, empty drums were discovered in trenches located approximately 200 ft north of the fire training pit (ESE, 1991). In June 1994, buried drums and associated contaminated soil were removed from the former burial trench (O'Brien & Gere Engineers, Inc., 1995). The investigations conducted under the RI/FS at Site FT-17 also confirmed the presence of contaminated residues in the vadose zone soil and a layer of LNAPL floating on the groundwater. The residual soil and LNAPL were identified as potential sources for groundwater and surface water contamination.

Groundwater samples collected during the RI/FS at Site FT-17 indicated the presence of a VC plume in groundwater extending from monitoring well MW-09S toward the Banana River (Figure 3-6). In addition, the analytical results from the RI/Fs sampling indicated that VC in groundwater is impacting surface water quality at the drainage canal that discharges to the Banana River. VC has not been detected immediately southwest of the canal. As a result, it appears that the drainage canal is intercepting the contaminated groundwater from Site FT-17.

Beginning in March 1996, a horizontal air sparging system was installed to intercept and treat the VC plume in groundwater to prevent the release of contaminants downgradient of the site. The overall objective of the horizontal air sparging system at Site FT-17 is to reduce VC concentrations to below 50 μg/L in groundwater, thereby reducing the concentration of VC in the adjacent drainage canal to below 1 μg/L.

The horizontal air sparging system (HASS) was installed by Horizontal Trenching Incorporated, which utilized a proprietary trenching and delivery operation that excavated a nominal 14" wide trench at FT-17. A vertical riser and horizontal well screen were installed to a depth of 30 ft bgs for Sparge Leg 4. The remaining sparge legs were installed approximately 25 ft bgs. During the excavation, in situ soil was removed, mixed and re-deposited in the trench. The horizontal air sparging system was designed as a sparge curtain with six overlapping horizontal well legs. The total length of the sparge curtain is approximately 1,163 ft. The sparge legs are constructed of 5-inch

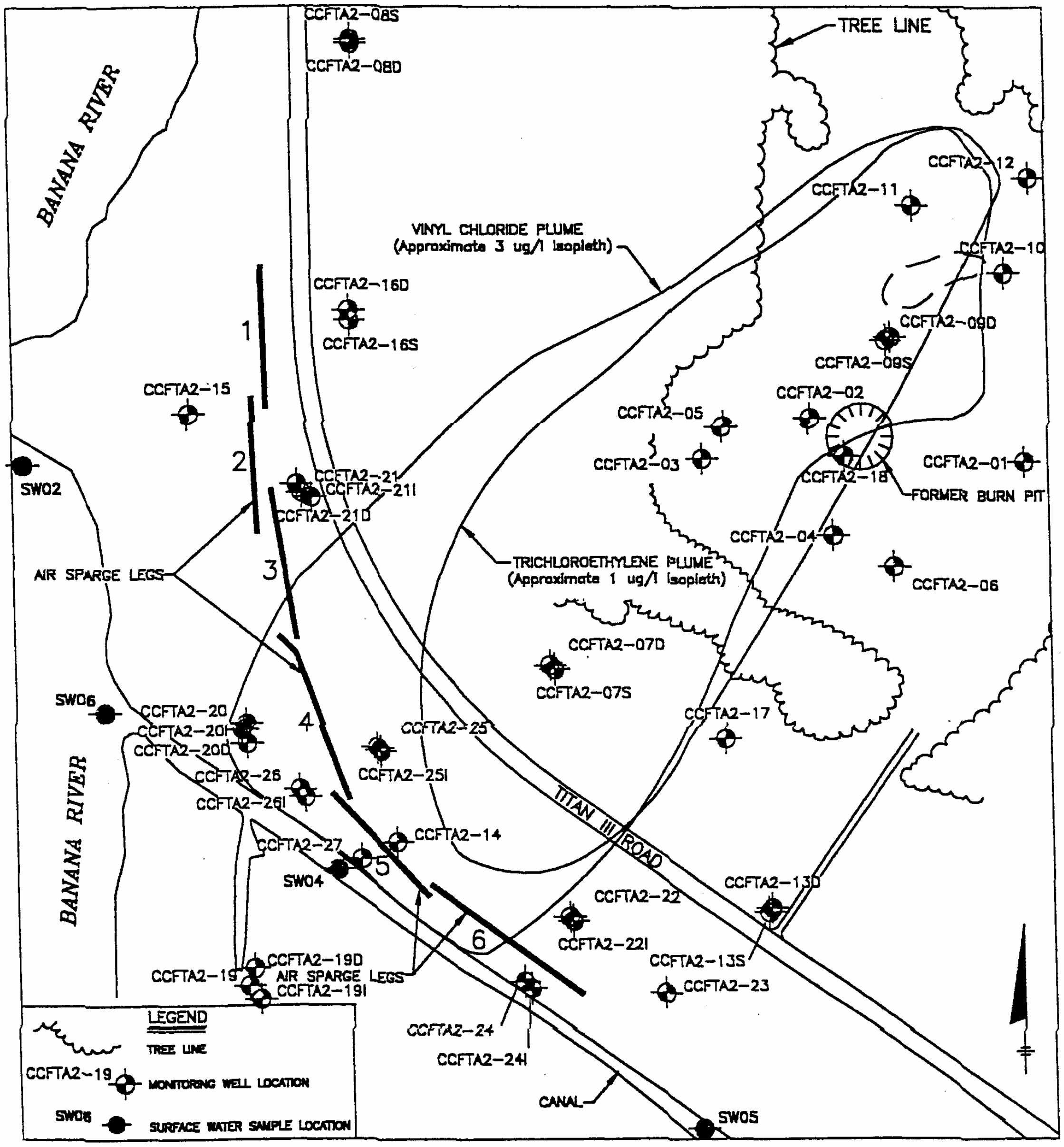



**Figure 3-6. Schematic Diagram of the Contaminant Plume and Horizontal Well Installations at Cape Canaveral AS, FL**

perforated, corrugated HDPE tubing with 0.125 by 0.75-inch slot size. Each sparge leg is encased in a two-ply polyester filter sock (450 micron) to prevent sediment infiltration.

The HASS consists of a 50 HP rotary vane air compressor capable of 325-scfm airflow at 25 psig. The outlet of the air compressor is routed through an aftercooler to a manifold that regulates airflow to each of the six legs by automated control valves. The compressor, associated electrical

equipment, and process controls are housed within a protective shed upgradient of the sparge curtain.

Monitoring equipment for the system includes pressure and flow meters to monitor airflow into the individual air sparge legs. In addition, conventional groundwater monitoring wells have been installed upgradient and downgradient of the air sparge curtain. The monitoring wells are designed to evaluate contaminant concentrations in the groundwater at the site.

**3.2.5 Department of Defense Housing Facility (DoDHF) Novato, CA.** DoDHF Novato is located in Novato, California, approximately 20 miles north of San Francisco in Marin County. The site, former UST Site 957/970, comprises an area of approximately 65 acres of land (an approximate rectangle with dimensions 2,800-ft by 1,000-ft) bounded on the south by Main Entrance Road, and on the north by a row of former storage bunkers south of Ammo Hill. The eastern border of the site runs north-south approximately 400 ft east of the intersection of Main Entrance Road and C Street, and the western border of the Site runs north-south approximately 600 ft west of the intersection of Main Entrance Road and C Street.

The Site is the location of a former NEX gasoline station and a Naval Public Works Center support area at DoDHF, Novato, California. Both the NEX service station and the PWC were supported by USTs that stored gasoline. The NEX service station tanks were identified with building 970 (the NEX service station building), and the PWC tanks were identified with former Building 957 (the PWC service station building). Because gasoline constituents in groundwater are not distinguishable by their former UST sources (i.e., the groundwater plumes have merged), the respective site designations were merged and the label "Former UST Site 957/970" (the Site) was adopted. At the northwest corner of Main Entrance Road and C Street on DoDHF Novato, Building 970 and associated pump islands were in use as a NEX gasoline service station from the mid-1970s through the early 1990s. At that time, the service station was closed and three USTs that had supported the station were removed. Another UST supporting the PWC service station was removed in 1992. Water and soils collected from excavations during tank removal activities indicated that gasoline had been released to the environment from USTs in both areas.

Soil characterization results indicate a heterogeneous site with sand, silt, gravel, and clays at varying proportions and depths. The top layer, which lays approximately 0 to 5 ft bgs, consists mostly of a sandy alluvial fill material. A sandy clay fill is encountered at 5 to 7 ft bgs. From 7 to 15 ft bgs, the aquifer zone consists of sands ranging from clayey sands to gravelly sands, but clay lenses are seen occasionally throughout the aquifer zone. The aquifer is underlain by bedrock at approximately 15 ft bgs but increases in depth north of State Access Road to a maximum depth of approximately 30 ft bgs. Observations show a water-bearing layer approximately 10 to 15 bgs consisting primarily of silt ranging from clayey silt to sandy silt.

At Former UST Site 957/970, a coupled in situ air sparging (IAS)/SVE system was installed to reduce the mass of hydrocarbon in selected areas. (The selected areas were designated as Areas A,

B, D, and E. Areas D and E are both small, and are therefore sometimes referred to together as Area DE.). The goal of the interim action was aggressive treatment of and removal of "hot spot" areas and mass reduction in areas in which the highest hydrocarbon concentrations were observed in groundwater. The interim action was performed because initial concentrations of benzene and MTBE exceeded protective concentrations as listed in the Tier 1 RBCA Assessment and lookup table values listed in ASTM E 1739 – 95 (Risk-Based Corrective Action [RBCA] Applied at Petroleum Release Sites). This effort was designed to reduce the potential of the groundwater plume to migrate and reduce hydrocarbon concentrations. The SVE system accelerated volatilization of hydrocarbons from the smear zone and vadose zone soils, and prevented the sparged vapor stream from being potentially emitted to the atmosphere or migrating subsurface to potential receptors.

The IAS/SVE system consisted of 18 air sparging wells and 13 SVE wells installed in May 1998. Sparge wells were screened as low as possible in the permeable layer to allow air to traverse the maximum possible distance through the impacted aquifer sediments. All air injection wells had 2 ft of screened area, with varying screened interval depth. Screened interval depths ranged from approximately 11 to 18 ft bgs. SVE wells were screened across the water table to accommodate fluctuations in groundwater levels. The screened interval for all SVE wells was 10 ft with the screened interval approximately ranging from 5 to 15 ft bgs. Figures 3-7 through 3-9 show the locations of air sparging and SVE wells in Areas A, B, and DE, respectively.

The major components of the air sparging system included two 25-HP air compressors and an injection airflow manifold panel for each compressor. The compressors were connected to the airflow manifold panels through a regulator and high-pressure gauge. The manifold panel consisted of the following components for each sparge well: a valve, a flowmeter (1 to 14 cfm), a regulator, and a pressure gauge (0 to 30 psi). Airflow and delivery pressure to each sparge well were controlled at the manifold panel. The panel mounts on the manifold were connected to the sparge wells with 1-inch-diameter, high-pressure air hose and associated fittings.

The major components associated with the SVE system included a regenerative blower, a 30-gallon moisture knockout drum for each SVE well, and an off-gas treatment system with a 500 scfm blower unit. SVE wells were connected to the off-gas treatment system with 2-inch-diameter PVC pipe and hose. A sampling port and vacuum gauge were installed on each knockout drum. A flowmeter and valve were installed in line from each SVE well to monitor and control the flow at each individual well. Sampling ports were installed on the pipe conducting vapor from each knockout drum, pipes conducting vapor from each area (A, B, D, and E), and on the overall combined flow manifold conducting vapor from the entire system.

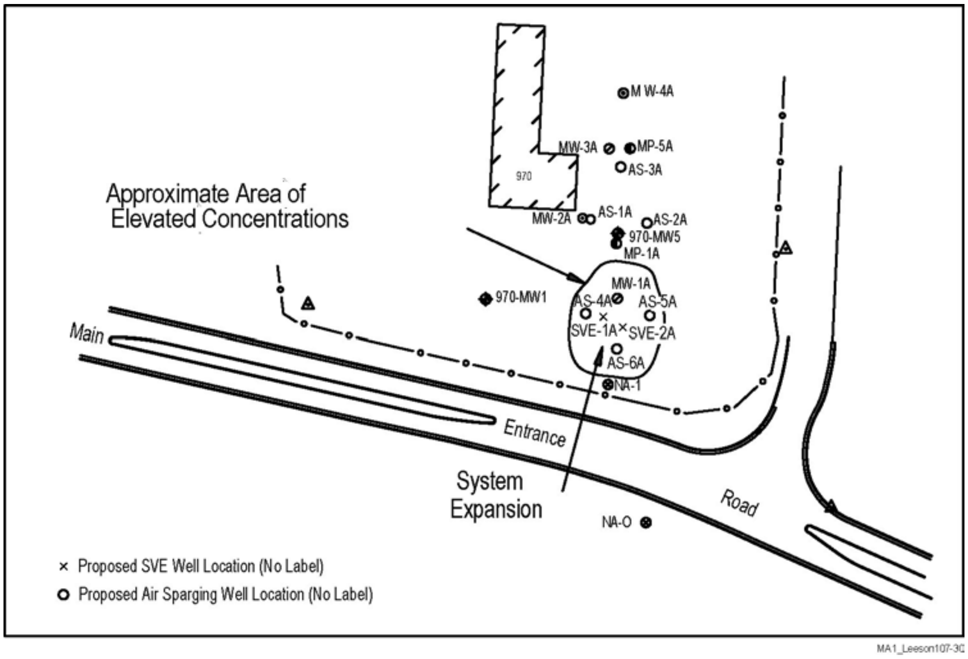
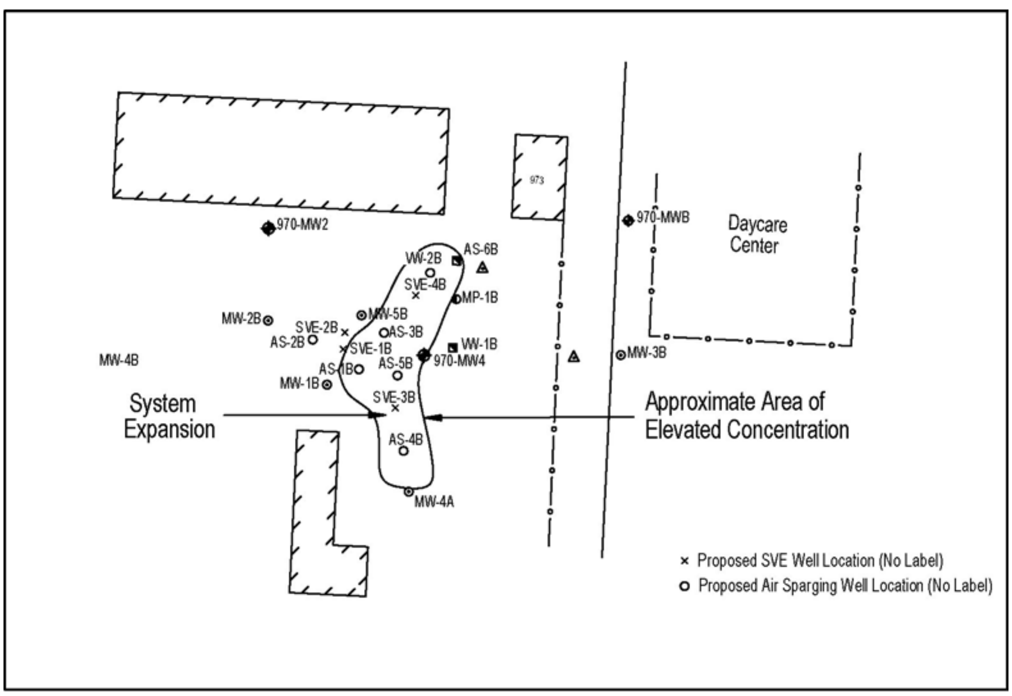



**Figure 3-7. Schematic Diagram of Area A, DoDHF, Novato, CA**



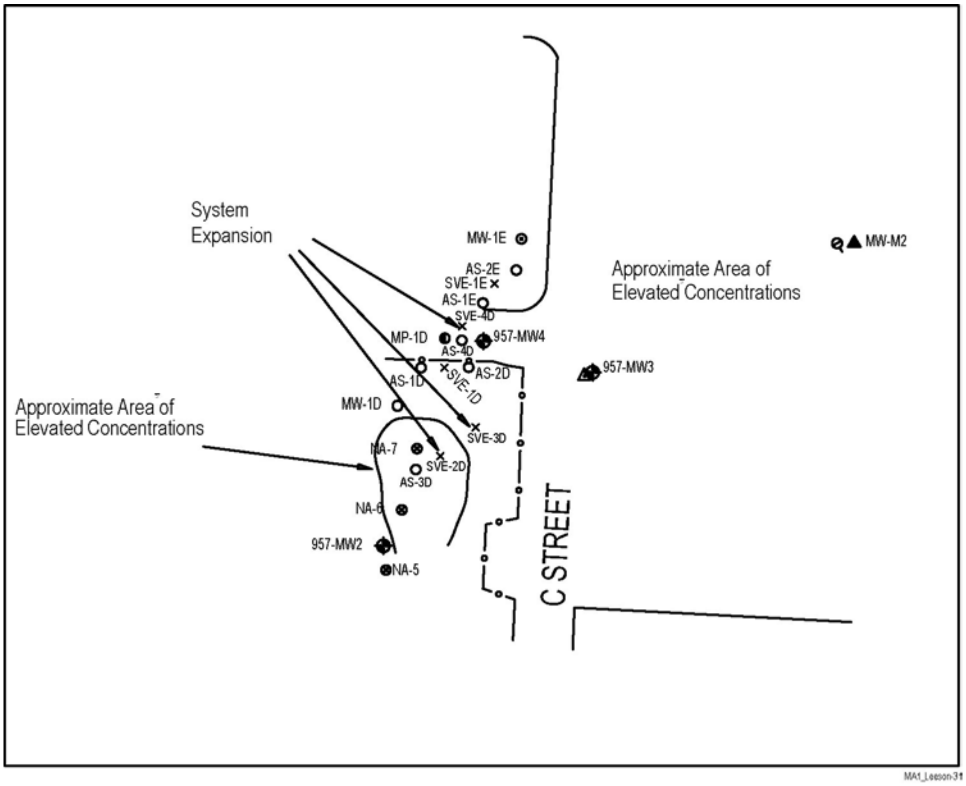



**Figure 3-9. Schematic Diagram of Area DE, DoDHF, Novato, CA**

**3.2.6 Marine Corps Air Station (MCAS) Fuel Farm, MCB Camp Pendleton, CA.** MCB Camp Pendleton is located almost entirely in San Diego County, California between the cities of Los Angeles and San Diego. The northwestern border of MCB Camp Pendleton is located in Orange County. The Base covers approximately 125,000 acres and is bordered on the west by the Pacific Ocean, with roughly 17 miles of coastline. Rolling hills and valleys extend inland 12 to 18 miles from the coastline to the northeastern limits of the Base.

The MCAS Fuel Farm is located in the Santa Margarita River Basin watershed at the southeast corner of the air station. The MCAS Fuel Farm was used to store jet propellant 5 (JP5) in aboveground storage tanks and fuel was pumped through subsurface piping to fueling stations located on the northeast end of the taxiway. Soil and groundwater contamination was discovered in 1993.

Groundwater at the site is found at a depth of approximately 8.5 ft bgs. Soil types generally are silty sands to a depth of 15 ft bgs, with some lenses of silty clay and sand interspersed throughout the site.

The air sparging system consists of 15 sparge wells and five soil gas and groundwater monitoring points. Sparge wells were generally installed to a depth of 15 ft bgs with a 1-ft screened interval.

The five monitoring points were nested with sampling intervals at 2.5 to 3 ft bgs, 4.5 to 5 ft bgs, and 10.5 to 11 ft bgs. Sparge wells were installed to treat areas with the highest contaminant concentrations. The system flowrate is 10 scfm per well operated intermittently in banks of five wells. A site diagram is shown in Figure 3-10.

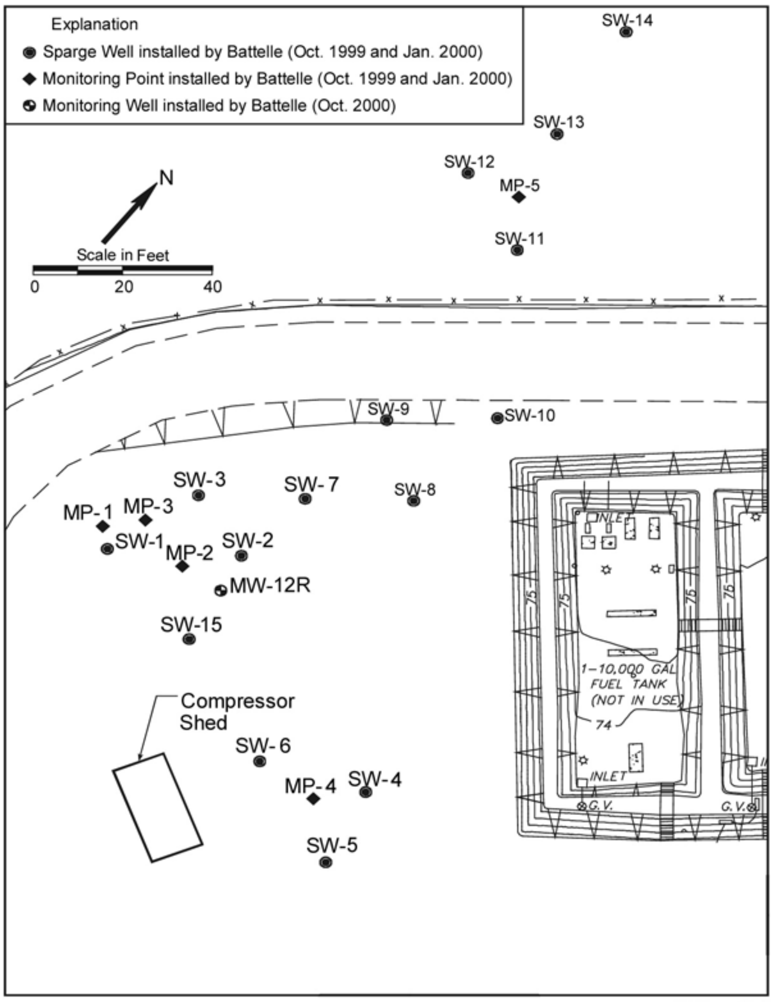



**Figure 3-10. ... ndleton, CA**

**3.2.7 Marine Corps Base Camp Lejeune, SC.** Site activities were conducted at Building LCH-4015. Building LCH-4015 is located in the Midway Park area of Marine Corps Base Camp Lejeune, NC. The site has served as a fuel farm and gasoline service station. Building LCH-4015 formerly contained one 3,000-gallon diesel fuel tank, one 14,000-gallon diesel fuel tank, and two 14,000-gallon gasoline tanks. Three 15,000-gallon gasoline tanks are located at SLCH-4024, located approximately ten ft southwest of Building LCH-4015 (Law, 1996).

The LCH-4015 site is relatively flat, sloping gently to the southwest, with an elevation of approximately 31 to 34 ft above sea level. Surface soils to 4 ft bgs typically consisted of silty, fine to medium sand with little clay. Very fine to fine sands, silty sands, and sandy clays were encountered from 4 to 10.5 ft bgs. Clayey sand to silty clay was encountered from 10.5 to 15 ft bgs. Silty sand with lenses of clayey sand was present from 15 to 40 ft bgs (Law, 1996). Groundwater at the site is shallow, less than 5 ft bgs.

The remedial system at Building LCH-4015 consists of an SVE unit in combination with an air sparging system. The air sparging system consists of 38 2-inch-diameter injection wells constructed at a depth of 8.5 ft bgs with a screened interval from 6 to 8.5 ft bgs. The SVE system consists of a series of horizontal extraction wells. A schematic diagram of the site is shown in Figure 3-11.

**3.2.8 McClellan AFB, CA.** McClellan AFB is located approximately 7 miles north of Sacramento, CA. In July 1987, the Base was placed on the U.S. EPA's National Priorities List. McClellan AFB is divided into 11 operable units, designated as OUs A through H, OU B1, OU C1, and OU GW. The demonstration was conducted at OU A, which has TCE concentrations in excess of 500 μg/L.

Activities were conducted at an existing air sparging site at McClellan AFB, CA from June 8 through 9, 2000. The air sparging system was installed at Operable Unit A (OU A), which is a former industrial degreasing facility contaminated with PCE and its daughter products, TCE and DCE. Depth to groundwater is approximately 110 ft and soils within the aquifer are primarily sand and gravel.

The system installed is a research project investigating the feasibility of injecting propane with air to promote cometabolic degradation of the chlorinated solvents in groundwater. Two test plots have been installed: an active test plot that receives propane with air and a control test plot that receives only air injection. Each test plot is constructed the same with one central injection well (screened from 118 to 120 ft bgs), 6 multi-level groundwater monitoring points (113 and 117 ft bgs), and 6 multi-level soil gas monitoring points. A schematic diagram of the site is shown in Figure 3-12.

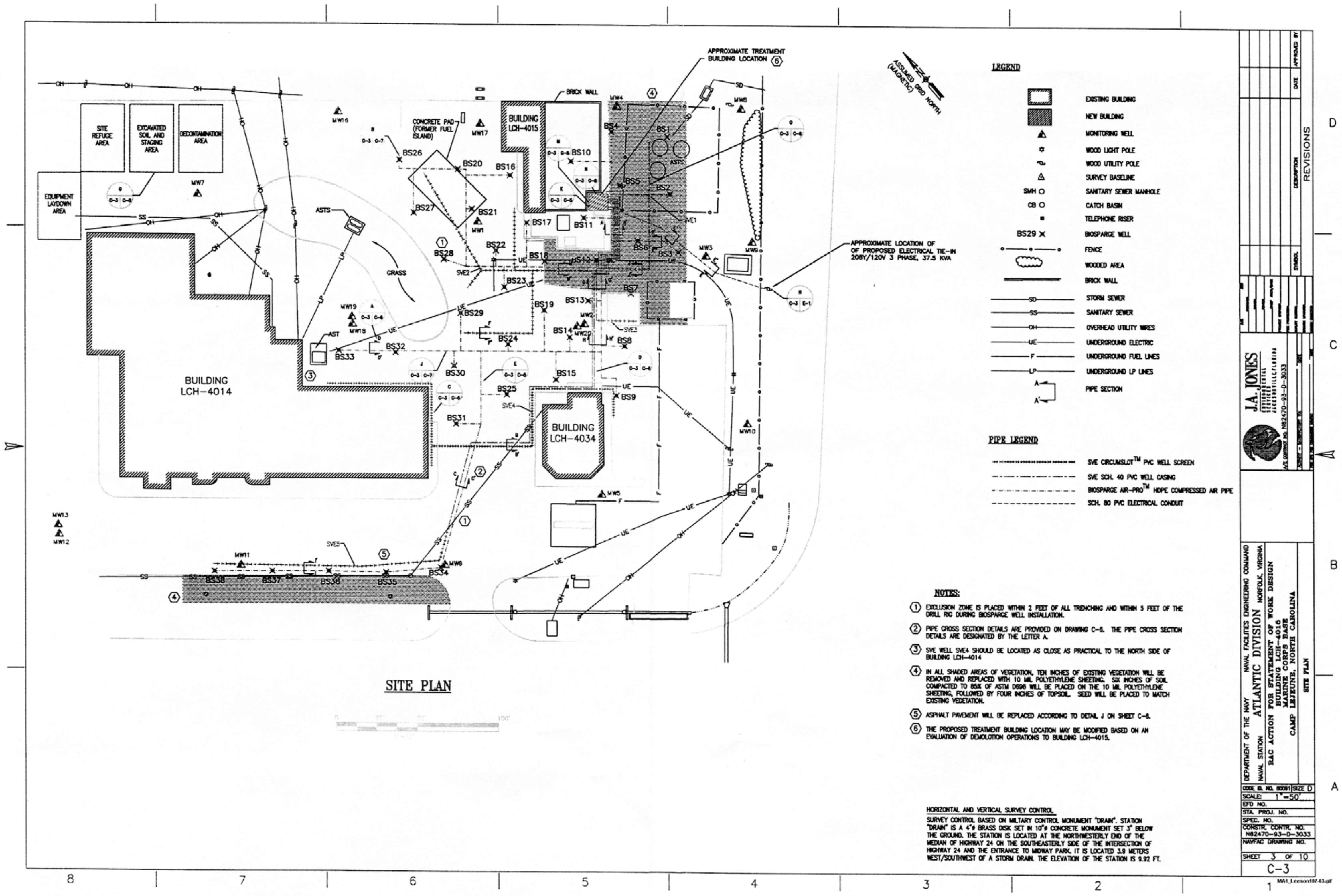



**Figure 3-11. Site Map Showing BuildingLCH-4015, MCB Camp Lejeune, SC (J.A. Jones Environmental Services Co., 1997)**

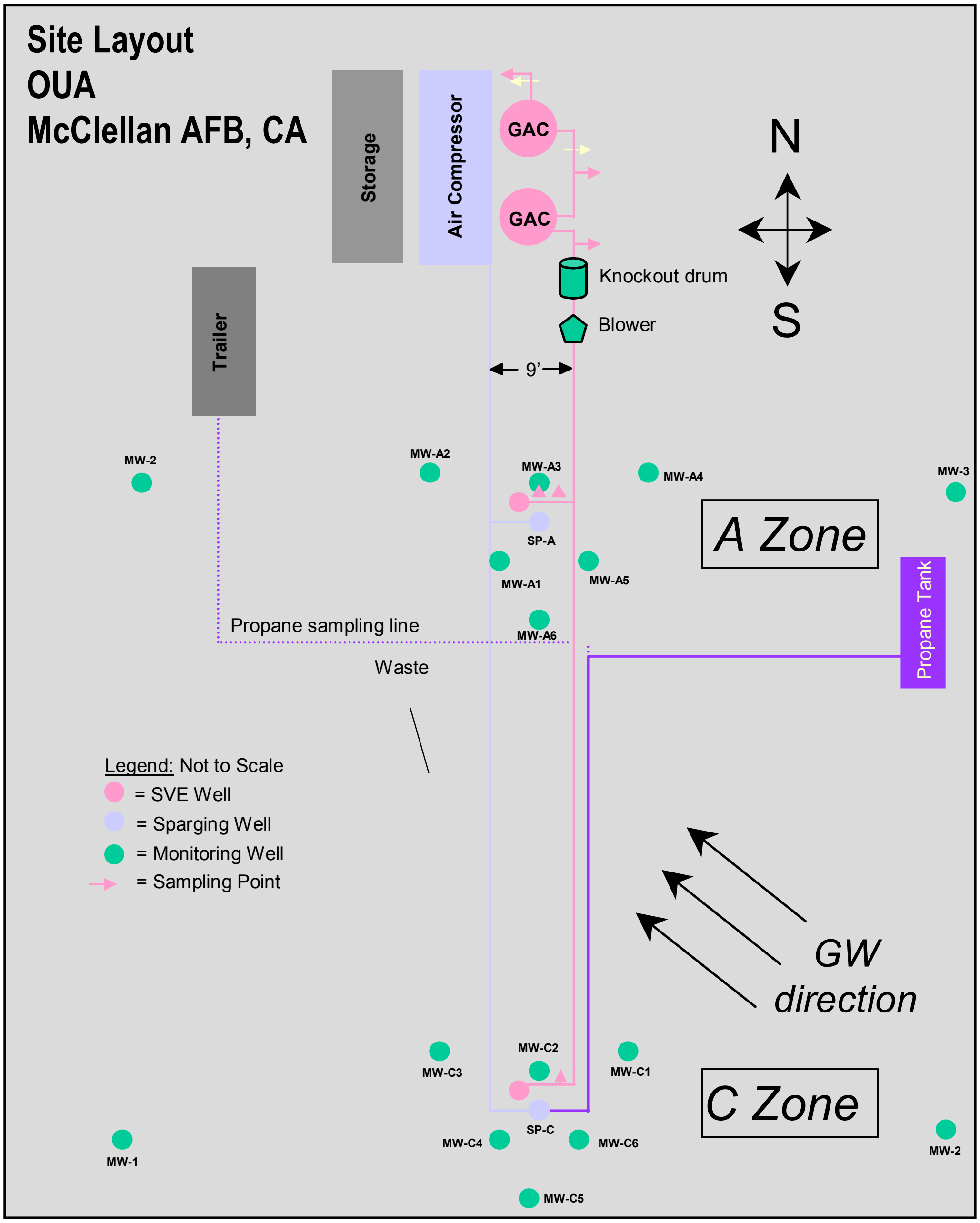



Figure 3-12. Schematic Diagram of OU-A, McClellan AFB, CA

**3.2.9 Operable Unit (OU) 6, Hill AFB, UT.** Hill AFB is located in northern Utah about 325 miles north of Salt Lake City and Approximately 5 mile south of Ogden. OU-6 is located in and adjacent to the northern part of Hill AFB. It includes buildings and adjacent land in the 1900 and

2000 Areas on Base, as well as portions of the Craigdale and Farr subdivision off Base. The 2000 Area is believed to be the source of the groundwater contamination.

There are at least three different aquifer systems underlying the demonstration area at OU-6. The uppermost aquifer (the focus of the demonstration) is first encountered at approximately 100 ft bgs. The deeper aquifers have potentiometric surfaces at approximately 210 and 320 ft bgs. There appears to be a thick section of principally clay strata separating the shallow aquifer from the deeper drinking water aquifer. Figure 3-13 illustrates an east-west cross section through the demonstration area. Cone penetrometer testing logs show that the shallow aquifer is predominantly sand. The sand is generally fine-grained with variable silt content.

Figure 3-14 illustrates the known extent of contaminated groundwater at OU-6 and shows the layout for the air sparging demonstration. A line of four sparge wells with co-located SVE wells was placed across a portion of the dissolved TCE plume that was exiting the base boundary (Radian, 1995). The sparge wells were installed with screened intervals from 128 to 132 ft bgs, while the SVE wells were installed with screened intervals from 94 to 99 ft bgs and from 65 to 68 ft bgs. In addition, nests of monitoring wells were distributed around the treatment zone. The monitoring wells had five screened intervals: two in the vadose zone and three in the saturated zone. Monitoring depths were 88 to 89 ft bgs, 98 to 103 ft bgs, 107 to 110 ft bgs, 117 to 120 ft bgs, and 127 to 130 ft bgs. The locations of the wells are shown in Figure 3-14. The total injection rate was approximately 50 scfm for the four wells while the total extraction rate was approximately 200 scfm.

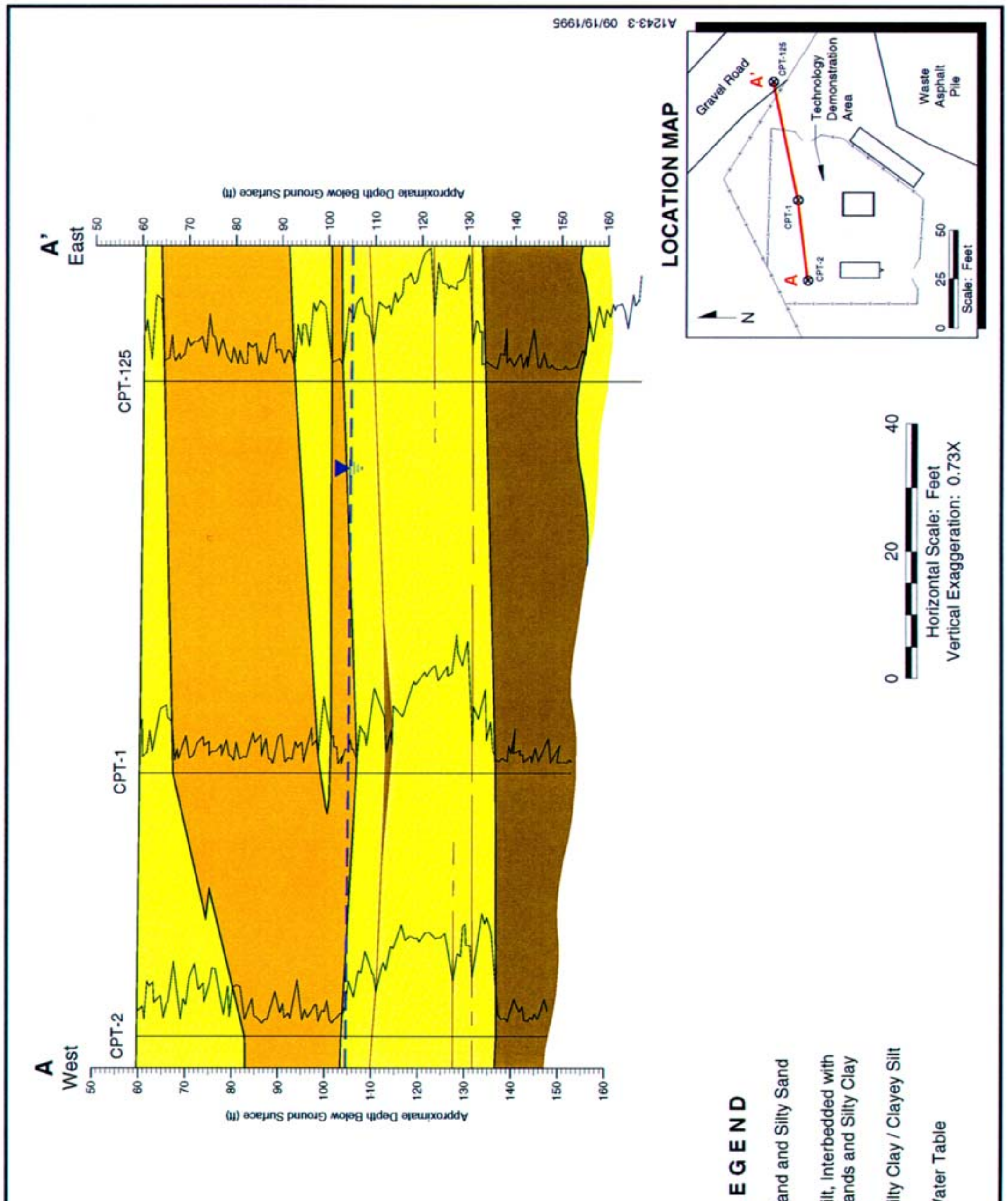



**Figure 3-13. Site Hydrogeology at OU-6, Hill AFB, UT**

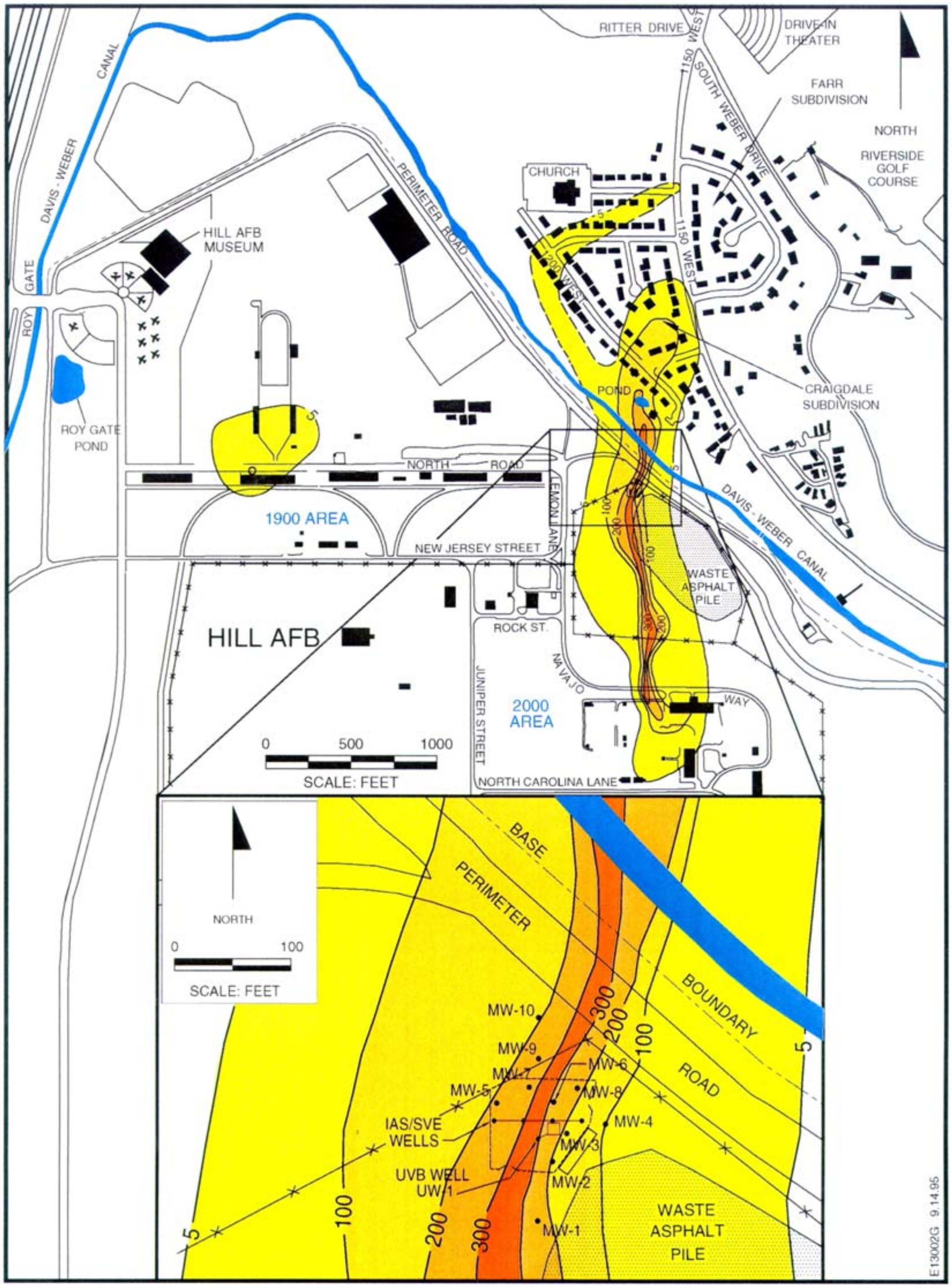



**Figure 3-14. Schematic Diagram of Installations at OU-6, Hill AFB**

# 4. Demonstration Approach

## 4.1 Performance Objectives

The primary performance objective was to implement the Air Sparging Design Paradigm at a number of existing air sparging sites and determine whether the Design Paradigm was effective at evaluating air distribution. The goal of the project was to modify the Air Sparging Design Paradigm as necessary based on results obtained from the 10 field sites.

## 4.2 Physical Setup and Operation

Existing sites were selected for evaluation. At five sites, no additional devices were installed (Camp Lejeune, Camp Pendleton, Hill AFB, McClellan AFB, and Novato). At four sites, groundwater monitoring points were installed (Cape Canaveral AS, Eielson AFB, Fairchild AFB, and Fort Lewis). At Port Hueneme, additional air injection wells were installed to bring the existing pilot-scale system up to a full-scale system; however, the current system was well-monitored and no additional monitoring devices were installed. The configuration, depth, and installation methods varied from site to site and are summarized in Section 3.2 in the individual site descriptions.

## 4.3 Sampling and Analytical Procedures

Sampling and monitoring procedures varied depending on site conditions and configuration. However, the following general guidelines were followed for every site. Table 4-1 identifies the activities that were conducted at each site. A summary of the activities conducted at the sites is provided in the following sections. Under the original scope of this project, five of the sites listed were intended for data evaluation only (Camp Lejeune, Camp Pendleton, DoDHF Novato, Hill AFB, and McClellan AFB). However, cost savings during the project allowed for collection of minimal data at these sites.

**4.3.1 Base-Line Monitoring.** Base-line monitoring generally included measuring groundwater/LNAPL levels, dissolved oxygen in groundwater; and mass transfer rate assessments.

**Table 4-1. Summary of Activities Conducted at each Site**

| Site | System | DTW (m) | Tests completed |
|---|---|---|---|
| Eielson AFB, AK | IAS | 2 | P, He, $SF_6$, P/P |
| Pt Hueneme, CA | IAS | 3 | P, $SF_6$, P/P |
| Fort Lewis, WA | IAS/SVE | 10 | P, He, $SF_6$ |
| Fairchild AFB, WA | IAS | 2 | P, He, $SF_6$ |
| Cape Canaveral AS, FL | IAS | 1 | P, He, $SF_6$ |
| Camp Lejeune, SC | IAS/SVE | 1 | P |
| Camp Pendleton, CA | IAS | 3 | P, He |
| DoDHF Novato, CA | IAS/SVE | 4 | P |
| Hill AFB, UT | IAS | 30 | P, He, $SF_6$ |
| McClellan AFB, CA | IAS/SVE | 30 | P, $SF_6$ |

DTW = depth to water; P = pressure testing; He = helium tracer testing; $SF_6$ = sulfur hexafluoride tracer testing; P\P = push-pull test

The depth to groundwater and apparent thickness of LNAPL in site wells were measured with an oil/water interface probe (ORS Model #1068013 or equivalent). The probe lead was a 50- to 200-ft measuring tape with 0.01-ft increments. The interface probe distinguishes between polar and nonpolar fluids in the well. The probe gives a solid tone when it encounters a nonpolar liquid (LNAPL) and a constant beep when it encounters a polar liquid (water).

Groundwater samples were collected using a low-flow peristaltic pump. Samples were measured for dissolved oxygen content under continuous flow using a dissolved oxygen meter (YSI Model 5776 Oxygen Probe or similar). In order to minimize aeration of the sample, a continuous flow-through cell was used to provide a sampling chamber for the meter. A sufficient volume of water from the well or groundwater sampling point was purged before sample collection to ensure that a sample representative of the formation is obtained.

**4.3.2 System Testing.** System testing was conducted to make an assessment of the feasibility of air sparging by examining air flow into the aquifer, air distribution around the sparge point, the effectiveness of the soil vapor extraction system, and safety issues. Air flow into the aquifer versus air injection pressure at a sparge point was monitored to evaluate varying pressure requirements necessary to achieve different flowrates into the subsurface. In addition, air injection pressure was monitored to record the minimum air entry pressure to induce flow into an aquifer. The air-entry pressure is heavily dependent on the type of geology at the site.

***Dissolved Oxygen*:** Monitoring increases in dissolved oxygen in the saturated zone is one approach in determining the effectiveness of the air sparging system for delivering air to the groundwater treatment zone. Groundwater samples were collected from the discrete groundwater sampling points prior to start up of the air sparging system and periodically during testing. Dissolved oxygen was measured according to the procedure described in the previous section.

***Sulfur Hexafluoride ($SF_6$) Tracer Testing:*** In these studies, $SF_6$ was blended with the air injection stream from the in situ air sparging compressor beginning approximately 24 hours after initiation of air sparging. $SF_6$ were injected continuously at a known mass rate for approximately 24 hours, at which time groundwater samples were collected to assess air distribution within the aquifer. The groundwater samples were collected from the discrete groundwater samplers. The concentration of $SF_6$ in the injected air was determined in the field. Based on the injection concentration, a theoretical solubility in the groundwater is calculated using a dimensionless Henry's gas constant of 150.

The $SF_6$ data do not give a direct measure of air saturation. Instead, the $SF_6$ data indicate where sparge air has been present in the groundwater zone during the period of its injection. In general, it can be assumed that concentrations near saturation indicate that air pathways were near the sampling point (e.g., within 10 to 20 cm based on the volume of groundwater sampled) and that zero or near-zero percent saturations indicate that air has not been in the vicinity of the sampling point.

***Pressure Transducer Measurements:*** Changes in groundwater levels in response to the air sparging were measured using pressure transducers and connected to a data acquisition system. A groundwater pressure transducer placed in existing groundwater monitoring wells, was used to monitor small fluctuations in the groundwater elevation. The pressure transducers used were from Instrumentation Northwest Inc., Redmond, WA (model PS9000, 0-5 psig) and were connected with a pressure transducer cable extension (Belden shielded cable, 1192A). The transducer is factory-calibrated and laboratory-tested. The pressure transducer has an accuracy of approximately ± 0.05 of full scale operating range. The pressure transducer was checked to ensure proper operation and utilized according to manufacturer's specifications. The data collection hardware was the PeakSimple Chromatography Data System, SRI Model 202 Four Channel Serial Port. Data was downloaded to a laptop computer using PeakSimple Software by SRI Inc.

The general procedure for conducting a pressure test was as follows:

- Place transducer into monitoring well
- Allow water level to stabilize
- Calibrate the transducer by raising a prescribed distance
- Start data acquisition system
- Start air sparging and monitor change in water table elevation in monitoring wells until pressure has stabilized (1 hour for shallow, 3 hours for deep or confined aquifers)
- Stop acquisition and start new data file
- Turn system off and monitor pressure decrease

***Helium Monitoring:*** The efficiency with which the sparge air is recovered by the SVE system can be determined using a helium recovery test. Helium is injected at a known concentration along with the sparge air. The concentrations of helium in the off-gas are monitored until it stabilizes. The efficiency with which the sparge air is recovered by the soil vapor extraction system can be determined using a helium recovery test. Helium is injected at a known concentration along with the sparge air. The concentrations of helium in the off-gas are then monitored until it stabilizes. The percentage of the air recovered is calculated as follows:

$$\% \text{ Air Recovered} = \frac{\text{SVE airflow}}{\text{Sparging airflow}} \times \frac{\text{Extracted concentration}}{\text{Injected concentration}} \times 100 \qquad (4\text{-}1)$$

This helium tracer test can also simultaneously be used to evaluate the degree of contaminant volatilization from the saturated zone, as well as determining approximately where air exits the saturated zone by measuring helium concentrations at the discrete vadose zone sampling points.

Helium in the soil gas was measured with a Marks Helium Detector Model 9821 or equivalent with a minimum sensitivity of 100 ppmv (0.01%). The helium detector is factory calibrated, but its accuracy is checked in the field with a standard to ensure proper operation.

# 5. Performance Assessment

A summary of the data collected from nine sites is provided in the following sections. The data from Port Hueneme is provided in a separate document in an attachment to the Air Sparging Design Paradigm (Appendix D).

## 5.1 Site ST10, Eielson AFB, AK

**5.1.1 Site Information.** The site at Eielson AFB did not have the type of installations required to conduct testing; therefore, the following equipment was installed as part of this field effort:

- 12 groundwater monitoring points were installed adjacent to existing sparge wells. These monitoring points consisted of a 1.25-inch-diameter, 6-inch-long screened interval with a stainless steel tube riser.

- A deep sparge well was installed adjacent to an existing sparge well. The new sparge well was constructed of 2-inch-diameter PVC and was screened from 18 to 20 ft bgs.

- Four SVE wells were installed around the paired sparge wells. The SVE wells were constructed of 2-inch-diameter PVC, and were screened from 3 ft bgs to 1 ft below the water table.

- Three groundwater monitoring wells were installed at 10, 20, and 30 ft from the sparge wells, and were used for pressure transducer measurements. The monitoring wells were constructed of 2-inch-diameter PVC with 10-slot screen from the water table to 10 ft below the water table.

- Twelve soil-gas monitoring points were installed within a 30-ft radius of the new sparge well. The soil-gas points consisted of a 6-inch long screen placed at 6 ft bgs with a ¼-inch diameter nylon tube connecting the screen to the surface.

A schematic diagram of the Eielson AFB test plot is shown in Figure 5-1.

Air sparging was conducted sequentially in the two sparge wells. Air injection rates were 5 scfm in the shallow well and 10 scfm in the deep well. The vadose zone at the site was quite fine-grained,

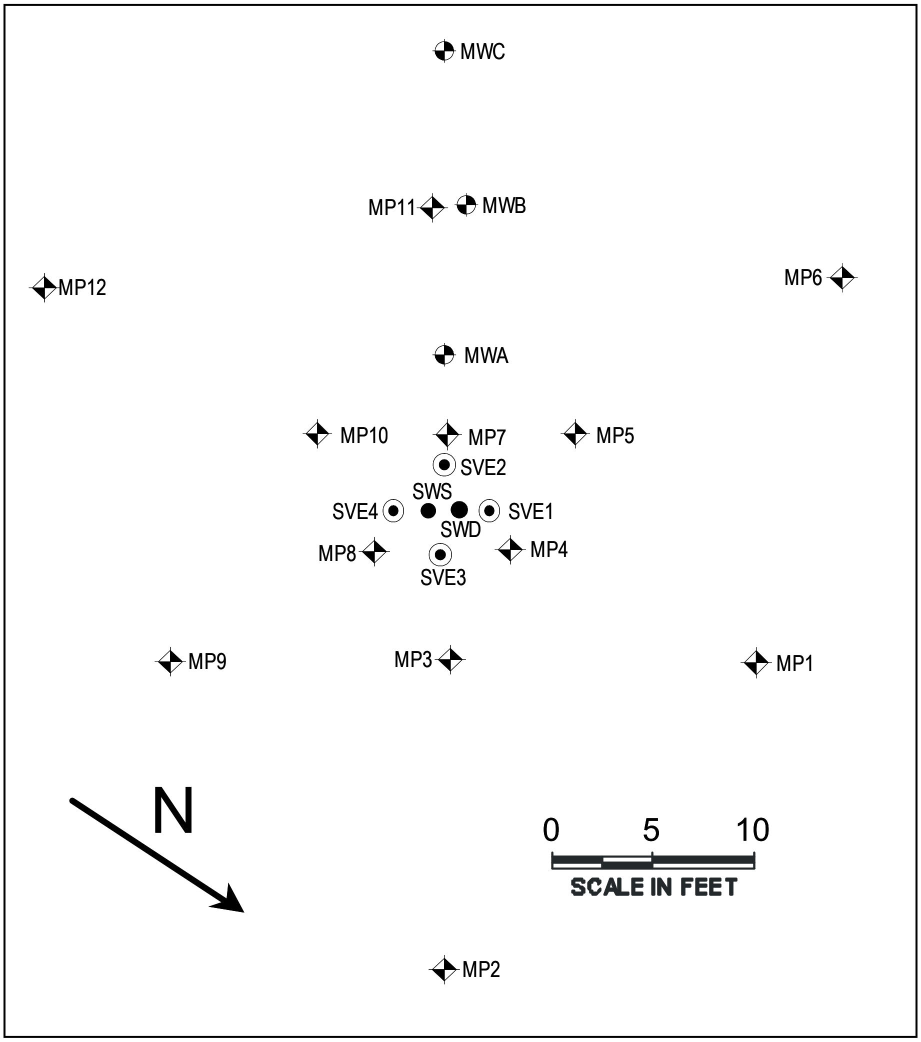



**Figure 5-1. Schematic Diagram of the Test Installations at Eielson AFB, AK**

and the maximum SVE rate that could be achieved without excessive upwelling of water was a combined total of 15 scfm.

**5.1.2 Results.** The diagnostic tests conducted at this site included: a) pressure response versus time; b) helium tracer testing; c) $SF_6$ tracer testing; and d) push-pull testing.

The groundwater pressure responses in the three monitoring wells to the injection of air into the shallow air sparging well at a rate of 5 scfm is shown in Figure 5-2a. The pressure changes are very small (e.g., <1 cm water), indicating a very-high permeability at that depth. Injection at 10 scfm into the deeper well (Figure 5-2b) shows an order of magnitude larger pressure increase than at the

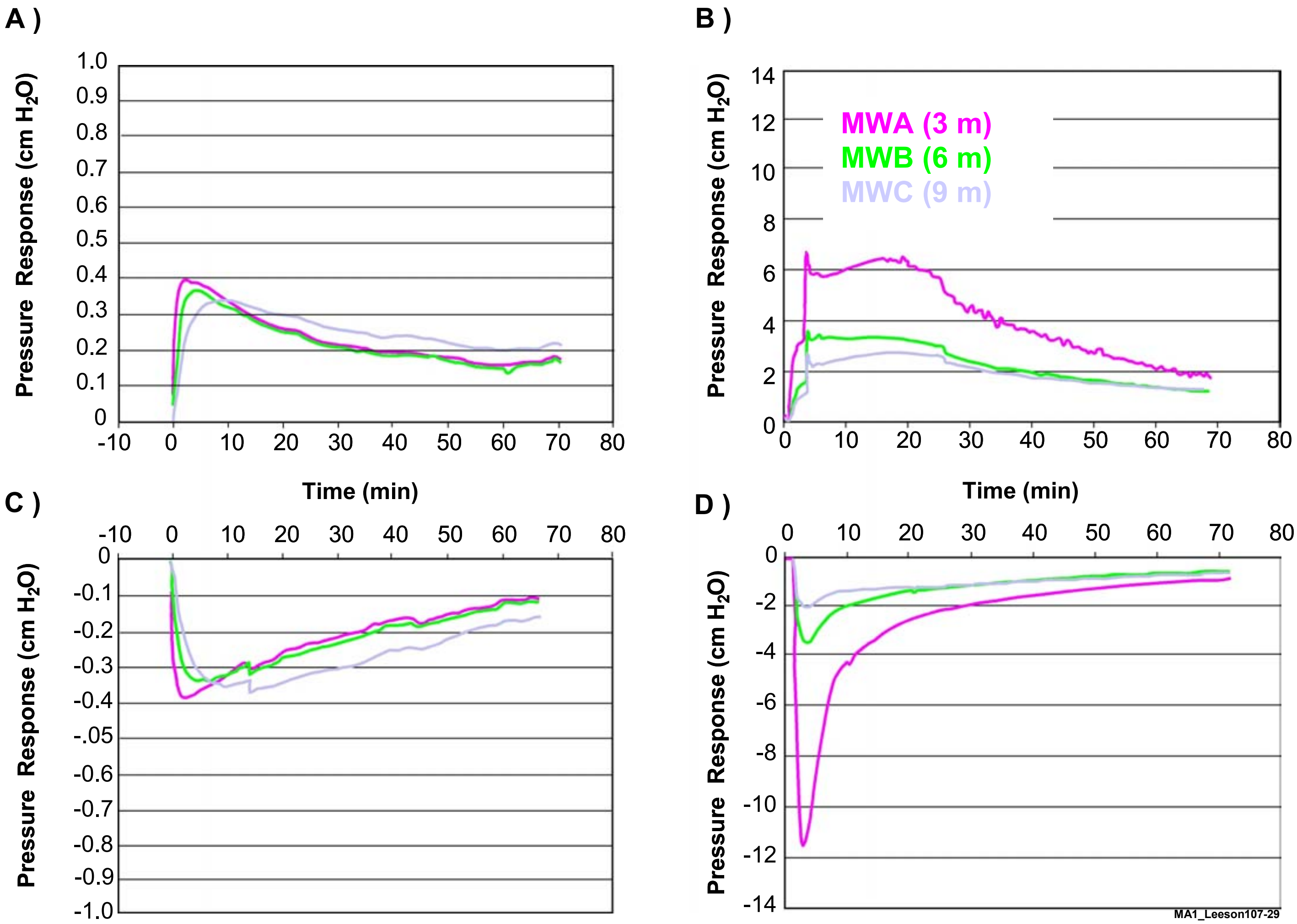



**Figure 5-2. Pressure Testing: A) Pressure Response at Initiation of Air Injection into the Shallow Well; B) Pressure Response at Initiation of Air Injection into the Deep Well; C) Pressure Response at Discontinuation of Air Injection into the Shallow Well; D) Pressure Response at Discontinuation of Air Injection into the Deep Well; Eielson AFB, AK**

shallow depth; however, the absolute value is still relatively small (e.g., <10 cm of water), indicating that the aquifer is still relatively permeable at the deeper depth. Groundwater pressure curves for air sparging shutdown at the two flowrates (Figure 5-2c and d) are similar in magnitude to the startup values. Also, the pressure data return to near-hydrostatic values within about an hour of startup and shutdown. This suggests that there was minimal stratification in the aquifer and that lateral migration of air will probably not be a problem at this site. However, pressure data alone cannot

assess the lateral extent of the air distribution at this or most other sites. As a consequence, the pressure data are best used in conjunction with other diagnostic data.

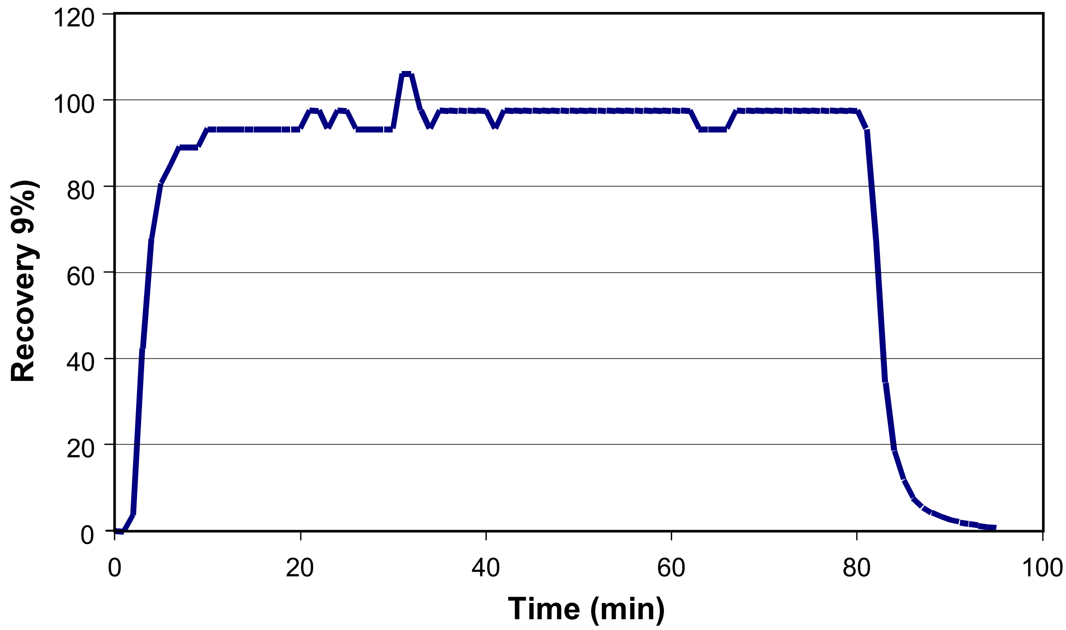
Helium recovery tests were conducted at 5 scfm in the shallow well and 10 scfm in the deep well. In both cases, the tracer quickly appeared in the SVE wells and the tracer concentration rose to approximately 100% recovery (Figure 5-3). When helium injection was stopped, the concentration quickly dropped. These data suggest that most of the air is exiting the water table relatively near the injection well.

To further evaluate the helium distribution, at the beginning of the recovery test, tracer concentrations in the deep vadose zone were monitored at 12 soil gas monitoring points, each at a depth of 6 ft (i.e., 2 ft above the water table). The deep vadose zone distribution data at the 5-scfm injection rate show that no helium was observed at any of the deep vadose zone points indicating that all of the air came up within a 5-ft radius of the well (Figure 5-4a). This supports the idea that there was little lateral migration of the air. When air was injected at 10 scfm into the deeper well screen, helium was observed at one location 10 ft from the sparge wells (Figure 5-4b). As a consequence, it can be concluded that some of the air reaching the water table was greater than 10 ft from the well.

To further assess the distribution of air in the subsurface, an $SF_6$ air distribution test was conducted. The $SF_6$ was injected for approximately 12 h and then samples were collected from each of the 12 groundwater monitoring points. The data in Figure 5-5 suggest that the air sparging air was widespread at a distance of 10 ft from the air sparging well, and was present in one monitoring point at 20 ft from the air sparging well.

To better understand the reasons for the difference between the helium and $SF_6$ data, $SF_6$ pulsed tracer tests (Bruce et al., 2001) were conducted in the vadose zone to determine transport times to the SVE well. Basically, for each test a known volume of $SF_6$ (a few mL) was injected into a monitoring point and its arrival time at the SVE well monitored. Based on simple geometric calculations, the time required for transport through the vadose zone to the SVE well can be calculated. Assuming that the thickness of the vadose zone is 8 ft, the distance from the SVE wells is 20 ft, the pumping rate is 15 scfm, and the air-filled porosity is 0.3, it should take about 200 minutes for the tracer to move to the SVE well. As the data in Figure 5-6 indicate, tracer injected at this distance arrived at the SVE well within approximately 50 minutes suggesting that there is preferential flow in the vadose zone. Since other data show the flow to be radially relatively symmetrical, and since the site is known to be overlain with finer-grained materials, the interpretation of these data are that vadose-zone air flow occurs primarily in the immediate vicinity of the water table. Since the vadose zone monitoring points are approximately 2 ft above the water table, and probably in the finer-grained materials, there may be bypassing of these points by the helium during the recovery test. These data once again point out the challenges associated with evaluating air sparging at real-world sites, as well as the importance of using multiple lines of evidence for those evaluations.

A)




B)

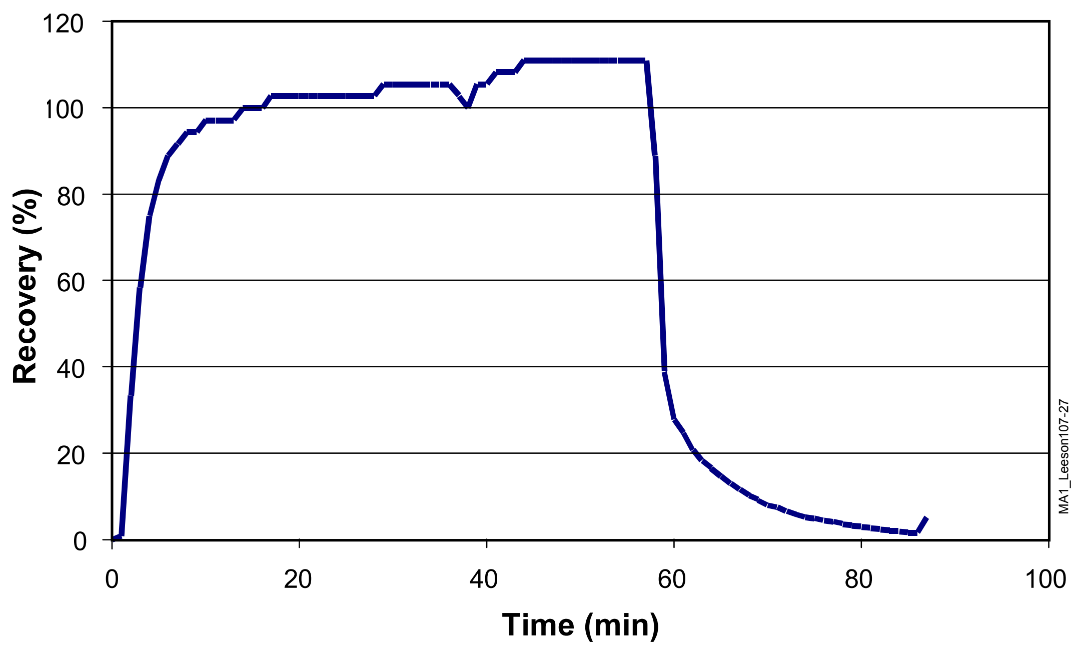



**Figure 5-3. Helium Concentrations versus Time in the SVE Off-Gas in A) the Shallow Injection Well; and B) the Deep Injection Well, Eielson AFB, AK**

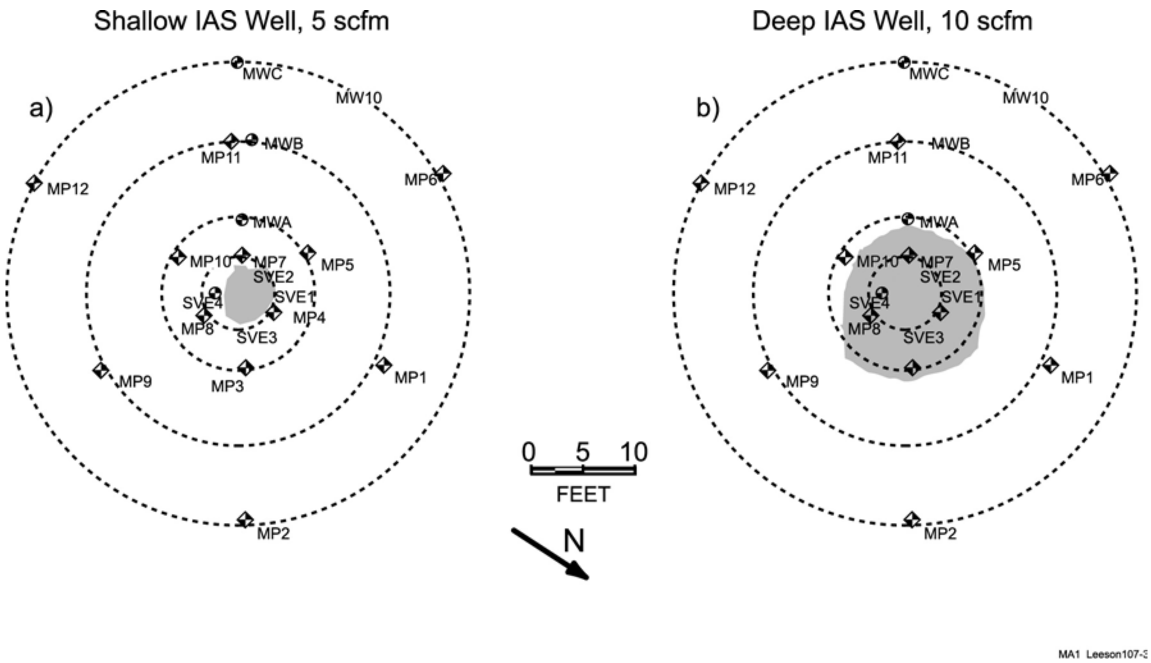



**Figure 5-4. Helium Appearance in the Vadose Zone During Tracer Testing in A) the Shallow Injection Well and B) the Deep Injection Well, Eielson AFB, AK**

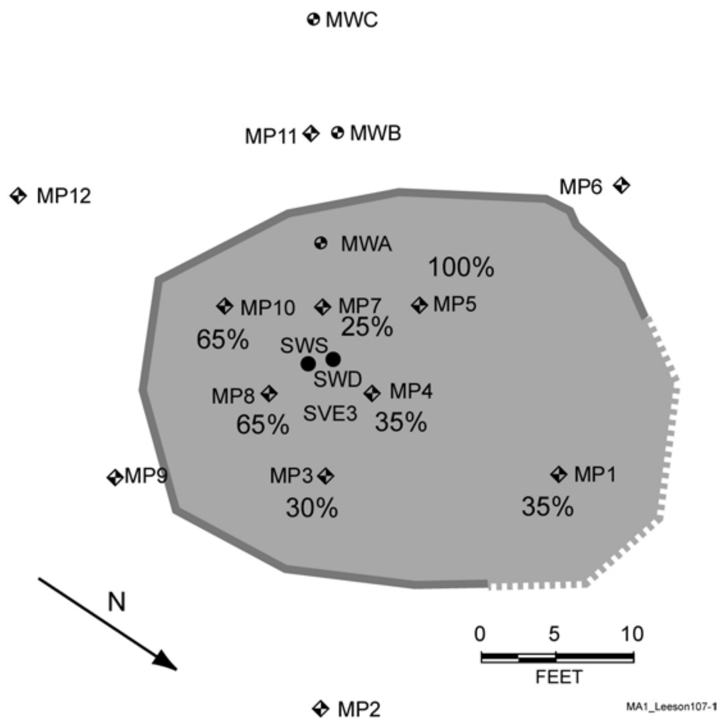



**Figure 5-5. Appearance of $SF_6$ in Groundwater Monitoring Points during $SF_6$ Tracer Testing in the Deep Injection Well, Eielson AFB, AK**

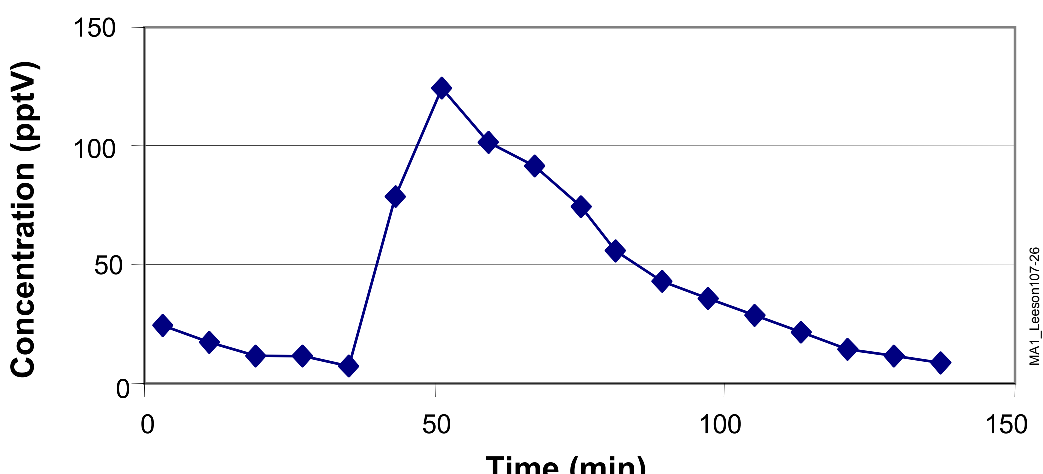



Figure 5-6. Results of Pulsed $SF_6$ Injection: Injection into a Monitoring Point and Recovery at the SVE Well, Eielson AFB, AK

At Eielson AFB, oxygen delivery and oxygen consumption tests were conducted in each of the groundwater monitoring locations. Dissolved oxygen concentrations were also measured at each of these locations. The dissolved oxygen and helium tracer data suggest an air flow distribution localized about the air injection well. The oxygen delivery and oxygen consumption test data were also consistent with the other diagnostic test observations. At this site both tests suggest possible oxygen transfer rates of about 20 to 100 mg-$O_2$/L per day in the zone affected by air flow (Figure 5-7.

**5.1.3 Summary and Conclusions.** Results from these tests indicate that the shallow sparge wells that were originally installed at the site impact an area less than 5 ft radially. The deep sparge well that was installed as part of this study impacted a larger area, up to 10 ft radially. Pressure tests, helium tracer studies, and $SF_6$ testing confirmed that the zone of influence was quite small around the injection wells, particularly at the shallow injection depth. While $SF_6$ tracer testing was able to confirm and clarify the results obtained with pressure and helium tracer testing, the data also was useful for solidifying the pilot testing portion of the Air Sparging Design Paradigm, where the more simple tests such as pressure and helium tracer testing are recommended.

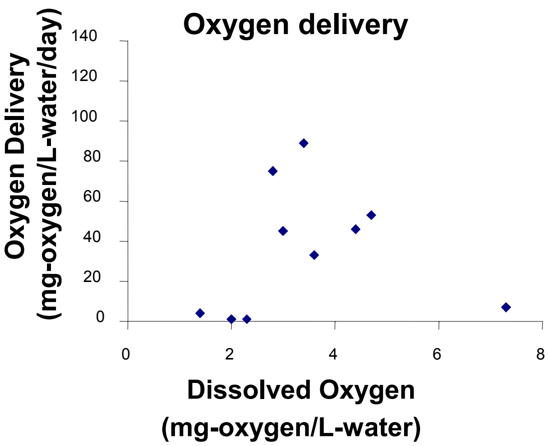
These results confirmed that the Air Sparging Design Paradigm recommendation for a 15-ft well spacing would have been sufficient to treat the site. The current installation has wells spaced approximately 100 ft apart and as such does not adequately treat the contaminated aquifer. The site is located well within the borders of the Base and groundwater does not flow near any Base housing. Given the size of the source area, natural attenuation is probably the most practical remediation technique for treatment of the contaminated plume, rather than installation of additional injection wells to expand the air sparging system.

## 5.2 Site FT-01, Fairchild AFB, WA

**5.2.1 Site Information.** The in situ air sparging chemical migration barrier (the "sparge fence") consists of 19 closely spaced air injection wells. These were installed in order to prevent migration of dissolved hydrocarbons emanating from a former fire training area. Groundwater at the site is shallow, with the water table found at 3 to 4 ft bgs and the bottom of the aquifer located at about 9 ft bgs. The system has historically been in continuous operation with a total air injection flowrate of approximately 200 scfm. At this site, flows to individual wells can be controlled via a manifolded system of valves; however, there are no in-line permanent direct-reading flow meters, and so flows to individual wells cannot be monitored in real-time.

Site FT-01 at Fairchild AFB did not have the type of installations required to conduct testing; therefore, the following installations were installed as part of this field effort:

- A total of six groundwater monitoring wells (GWMWs) were installed. GWMW-5 was placed 3 ft south of the sparge curtain, while GWMW-1 and GWMW-6 were



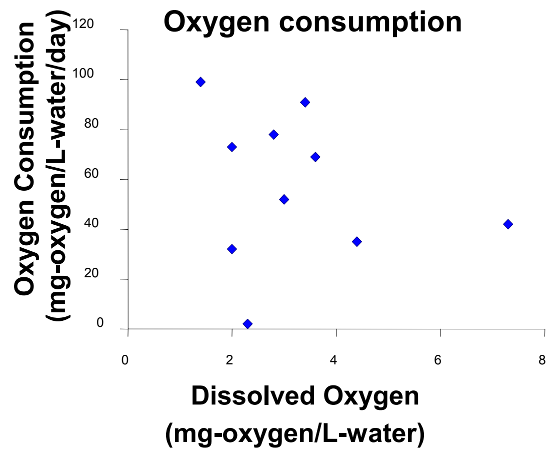




**Figure 5-7. Oxygen Delivery and Oxygen Consumption Results at Eielson AFB, AK**

placed between wells within the sparge curtain. GWMW 2, 3 and 4 were arranged in a line extending downgradient from the sparge curtain. The groundwater monitoring wells were screened from 7 to 9 ft bgs.

- 15 groundwater monitoring points/soil-gas monitoring points were installed in various locations upgradient and downgradient of the sparge curtain. These installations consisted of a groundwater monitoring point with 1-inch diameter 10-slot screen from 5 to 7 ft bgs and a soil-gas point at 2 ft bgs. Two additional groundwater monitoring points were placed at 60 ft upgradient and downgradient from the curtain. Soil-gas monitoring points were not installed at these locations.

A schematic diagram of the installations is shown in Figure 5-8.

**5.2.2 Results.** Diagnostic tests were performed during two site visits. During the initial visit, diagnostic tests included: a) system flowrate measurements using a helium dilution method; b) pressure transducer responses; and c) $SF_6$ distribution in groundwater measurements. An overall system push-pull and air distribution tests were not conducted, given the poor air distribution to the system of wells, and the lack of flow monitoring devices that would allow proper adjustment of the air flows to individual wells.

Startup and shutdown pressure transducer response tests were conducted with flow only into one injection well (Well 15) and with flow into the entire system. The flowrate to Well 15 was approximately 25 scfm (based on helium dilution tests). Pressure changes of about 30 cm (1 ft) of water were observed in the vicinity of the well. Pressure returned to static conditions within about

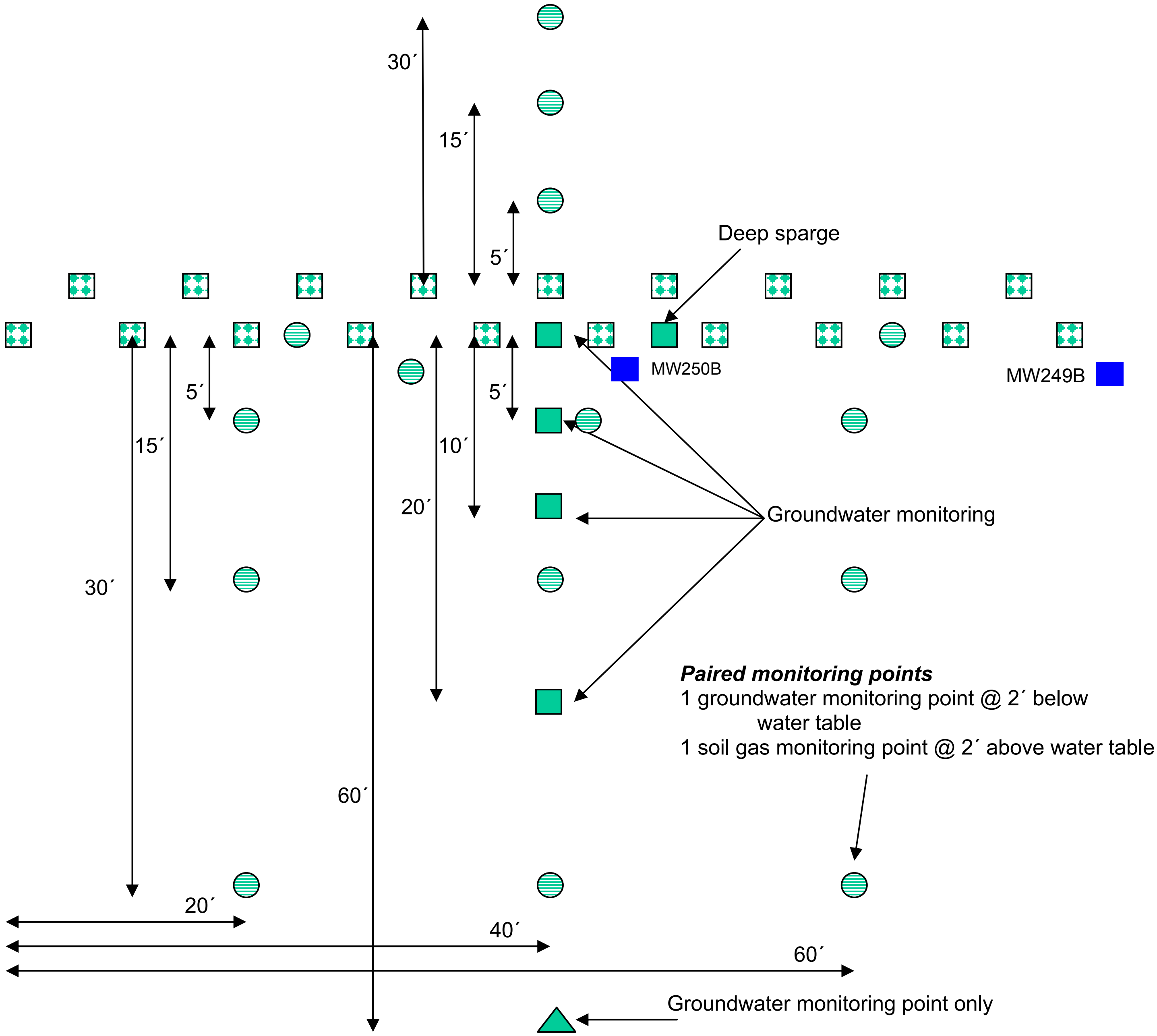



**Figure 5-8. Schematic Diagram Showing the Locations of Monitoring Wells Around the Sparge Curtain, Fairchild AFB, WA**

15 minutes, indicating that steady-state airflow was quickly established (Figure 5-9). The data suggest that there are no significant stratigraphic barriers to airflow. Data from operation with injection into all wells yielded similar results (Figure 5-10). Based on the depths of the wells and previous experience, we would estimate that the radial extent of air distribution about the air injection well(s) is less than or equal to 5 ft. This is consistent with the reported site geology and well construction.

An $SF_6$ air distribution test was also conducted on Well 15. A low concentration of $SF_6$ was added to the injection air for a period of 12 hours. Dissolved $SF_6$ concentrations were then measured in the Geoprobe™ implants installed for this study. No significant $SF_6$ was found in any of the implants indicating that the zone of influence was probably less than 5 ft.

During the second site visit, the performance of individual injection wells was tested. Due to the lack of direct reading flow meters and subsequent uncertainty in air injection flowrate distribution throughout the sparge fence system, a helium tracer test was first conducted to measure the flow in individual wells during steady-state operation. In each test, helium was metered to an individual injection well at a known flowrate at a point just down stream from the manifold (this test was ultimately repeated for each air injection well). The concentration of helium was then measured in the injection air at the air injection wellhead. The flowrate in that well was calculated by dividing the known helium flowrate by the volume fraction of helium measured in the injected air. Simultaneously, pressure response was measured in two monitoring wells: MW249 and MW 250.

This test revealed that only 8 of the 19 air injection wells had air flowing through them, and of those 8, the flow was dominant in 3 to 4 of the wells. Significantly, the air injection wells upgradient from the permanent groundwater compliance monitoring points were among the group of wells that had no air injection flow. Pressure testing of the non-flowing wells suggested that the screens were plugged (Figures 5-11 through 5-20). Based on conversations with Fairchild AFB personnel, it is likely that they have been plugged since installation.

**5.2.3 Summary and Conclusions.** The $SF_6$ tracer test and the pressure testing indicated a relatively small zone of influence around the sparge wells. This data supports the Air Sparging Design Paradigm guidance of close well spacings to ensure adequate site treatment. In addition, it further supports the pilot testing guidance to use a simple pressure test to examine air distribution.

Based on the results of the diagnostic tests, the following changes in system design and operation are recommended:

1. We recommend that, due to the shallow depth to groundwater, that a trench should be dug, backfilled with pea gravel, and the wells reinstalled.

A)

B)

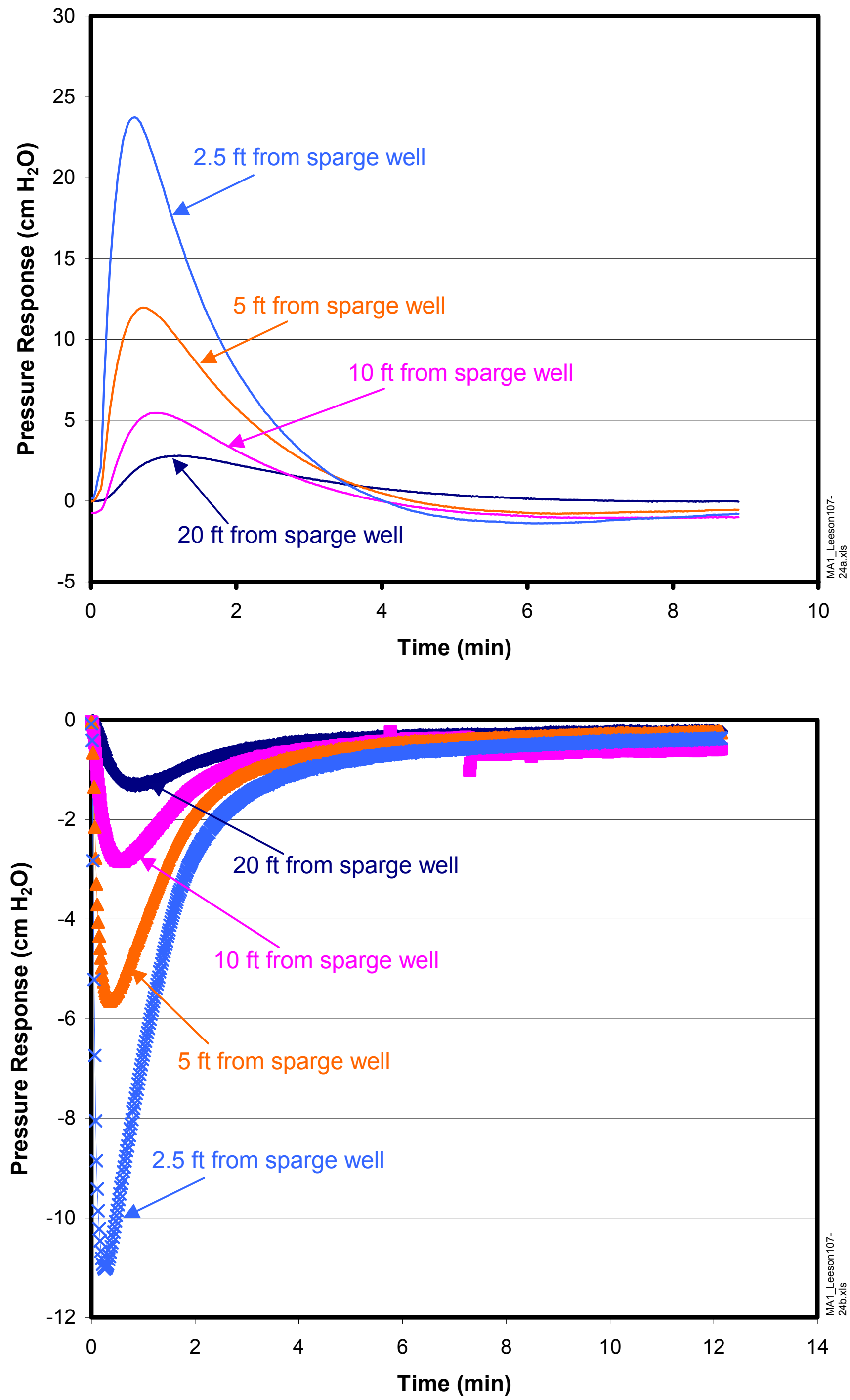
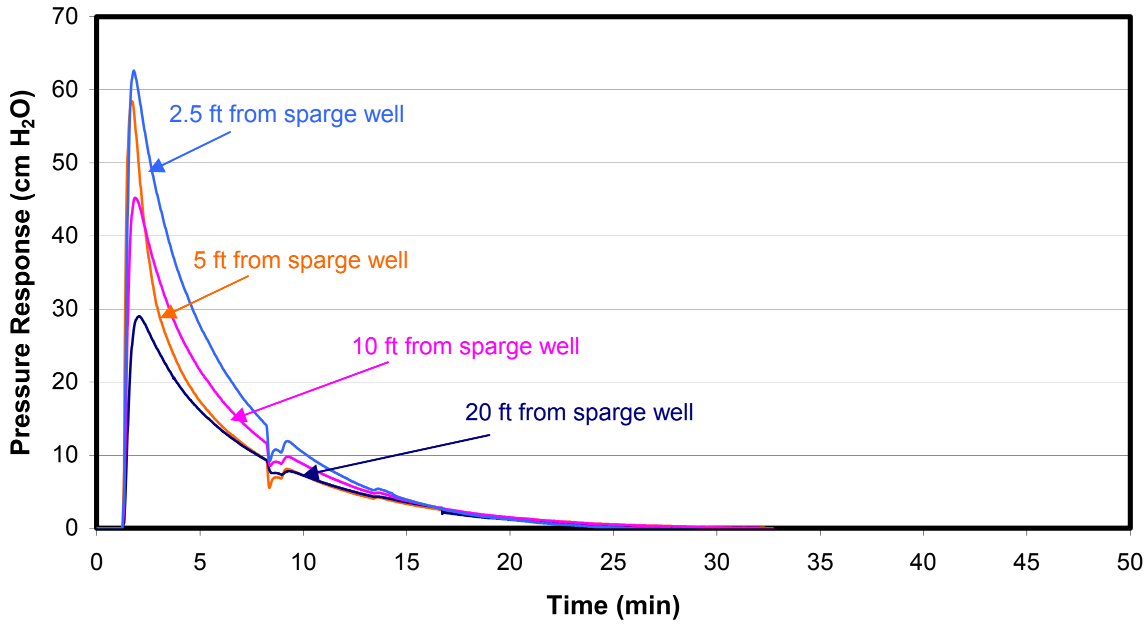



**Figure 5-9. Pressure Response versus Time during Injection into Sparge Well 15 at Start-Up (A) and Shutdown (B) of Air Injection, Fairchild AFB, WA**

A)

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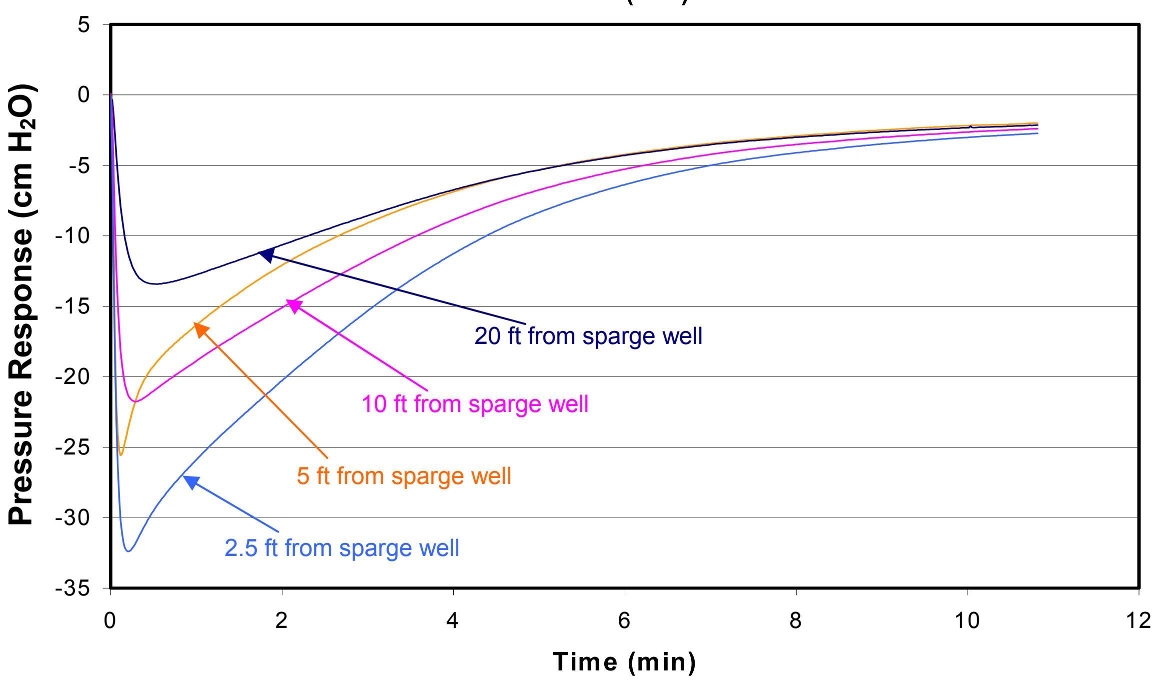



**Figure 5-10. Pressure Response versus Time during Injection into All Sparge Wells at Start-Up (A) and Shutdown (B) of Air Injection, Fairchild AFB, WA**

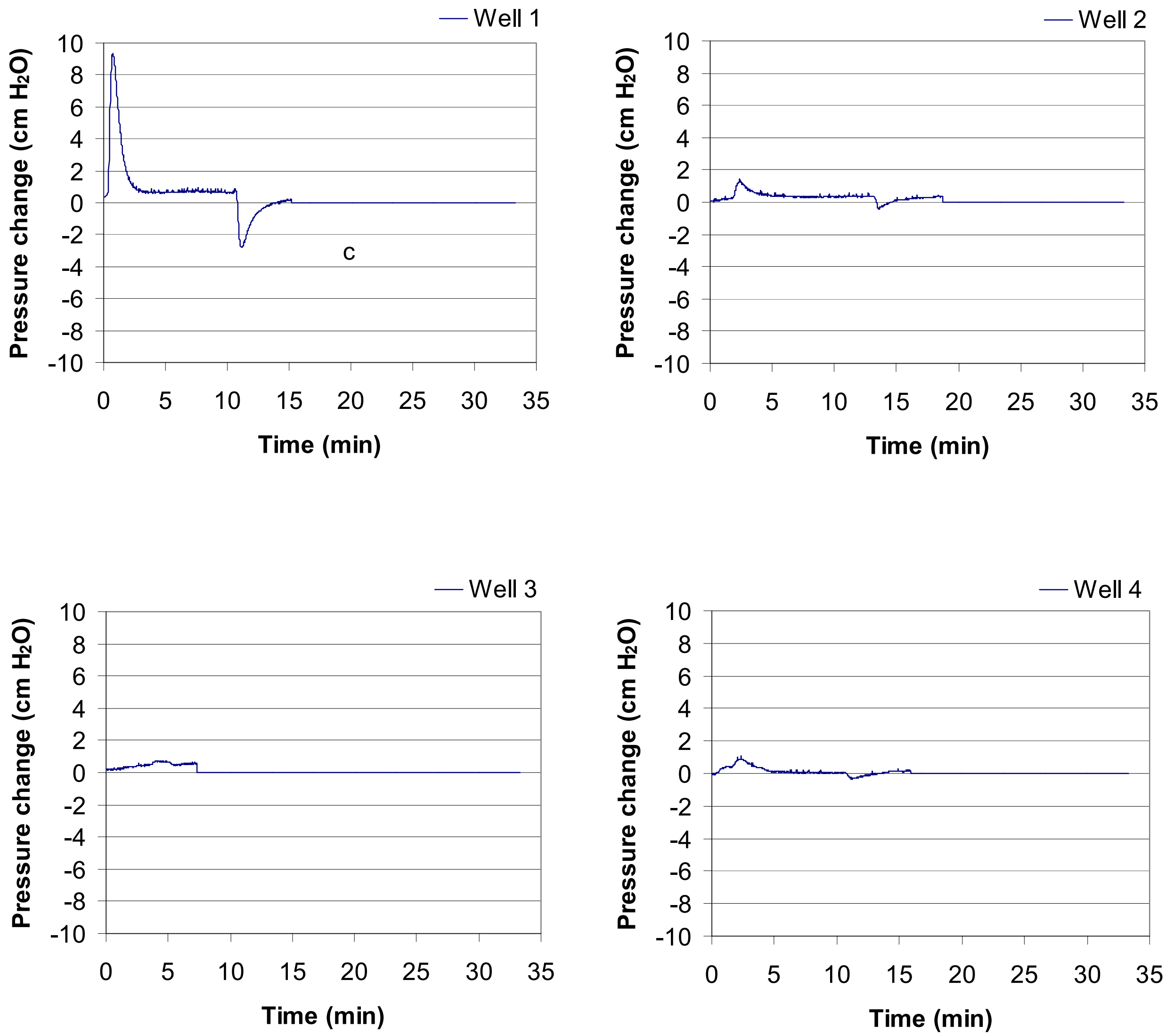



**Figure 5-11. Pressure Response in MW249 versus Time during Injection into Sparge Well 1, 2, 3, and 4, Fairchild AFB, WA**

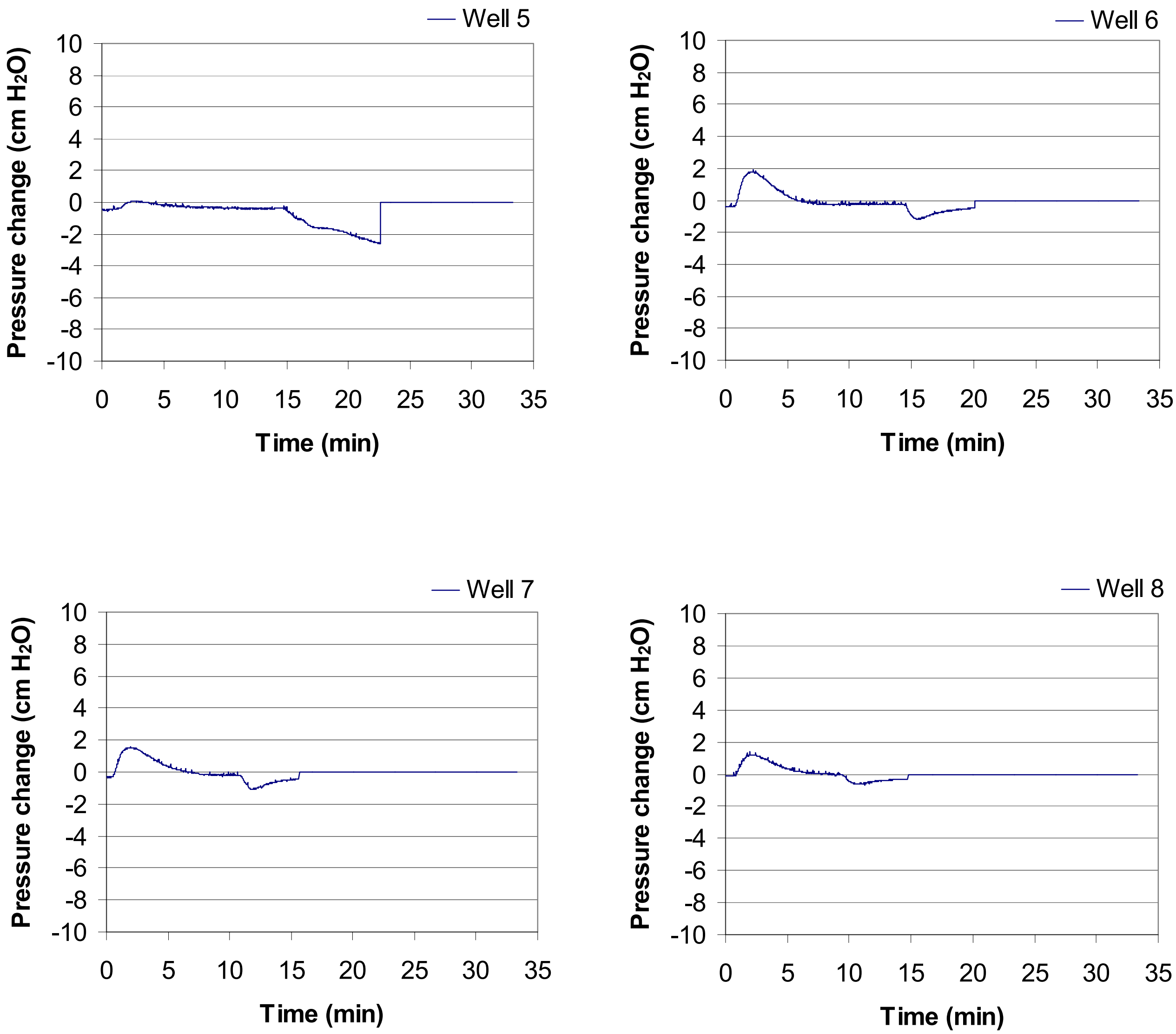



**Figure 5-12. Pressure Response in MW249 versus Time during Injection into Sparge Well 5, 6, 7, and 8, Fairchild AFB, WA**

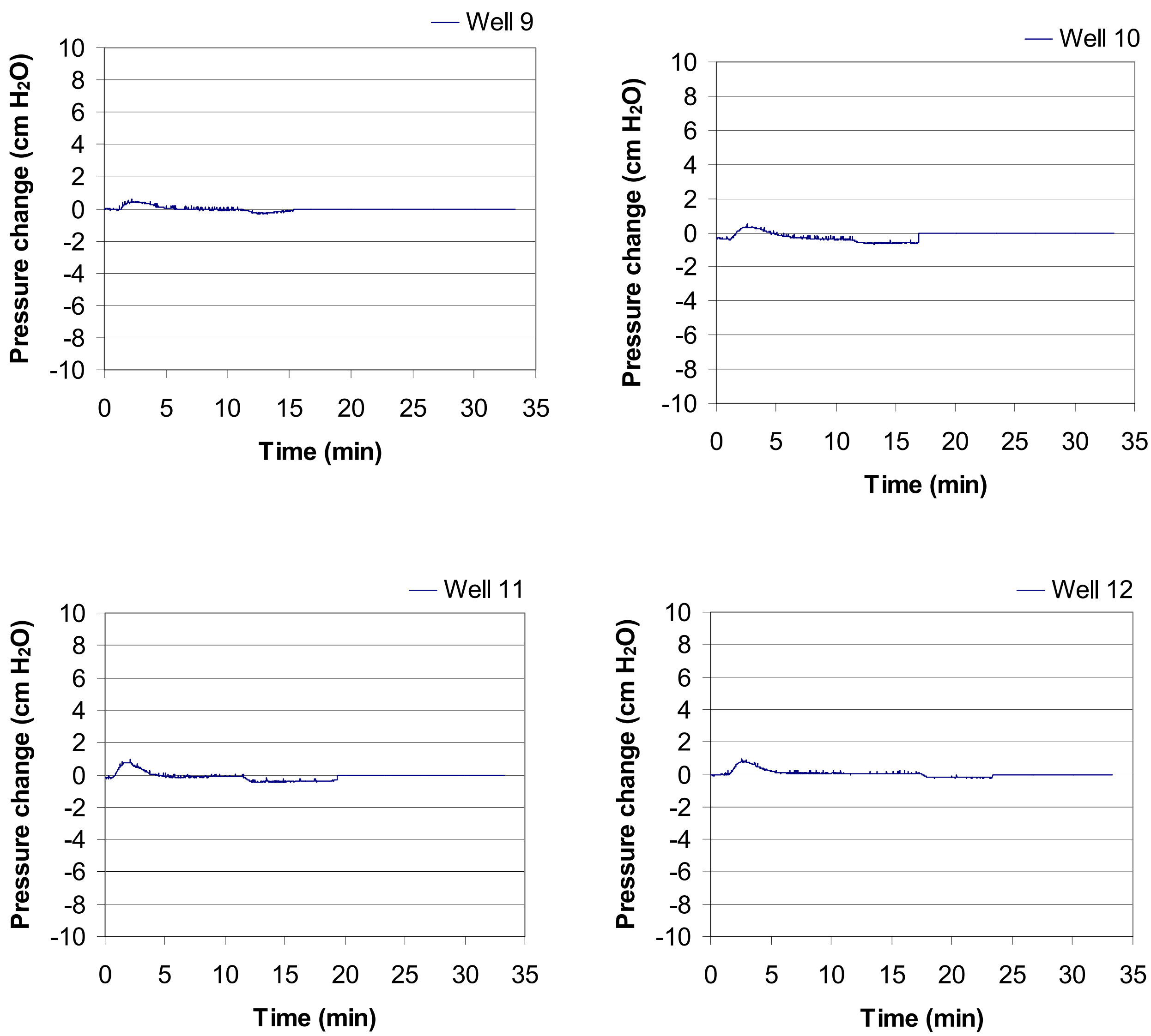



**Figure 5-13. Pressure Response in MW249 versus Time during Injection into Sparge Well 9, 10, 11, and 12, Fairchild AFB, WA**

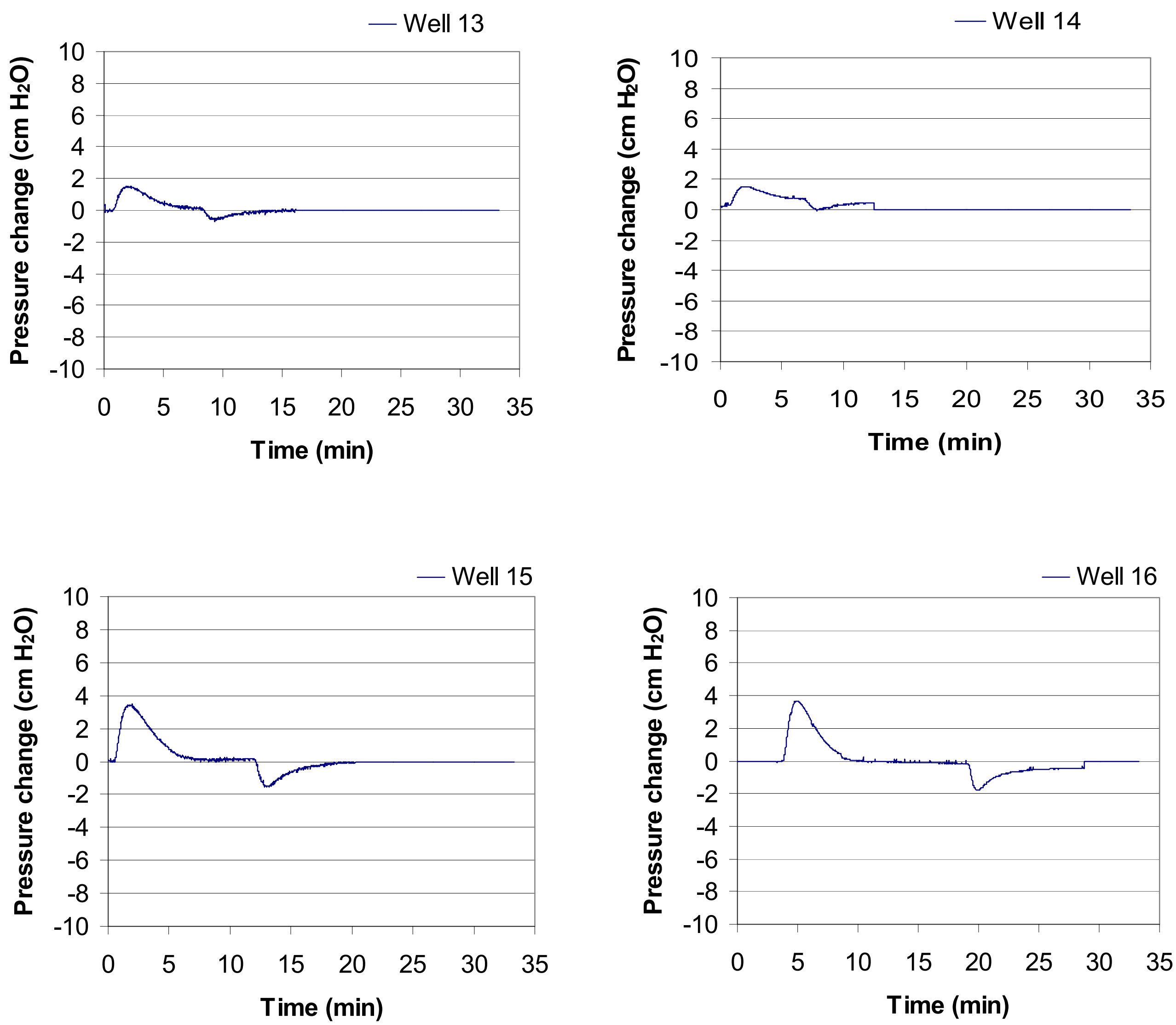



**Figure 5-14. Pressure Response in MW249 versus Time during Injection into Sparge Well 13, 14, 15, and 16, Fairchild AFB, WA**

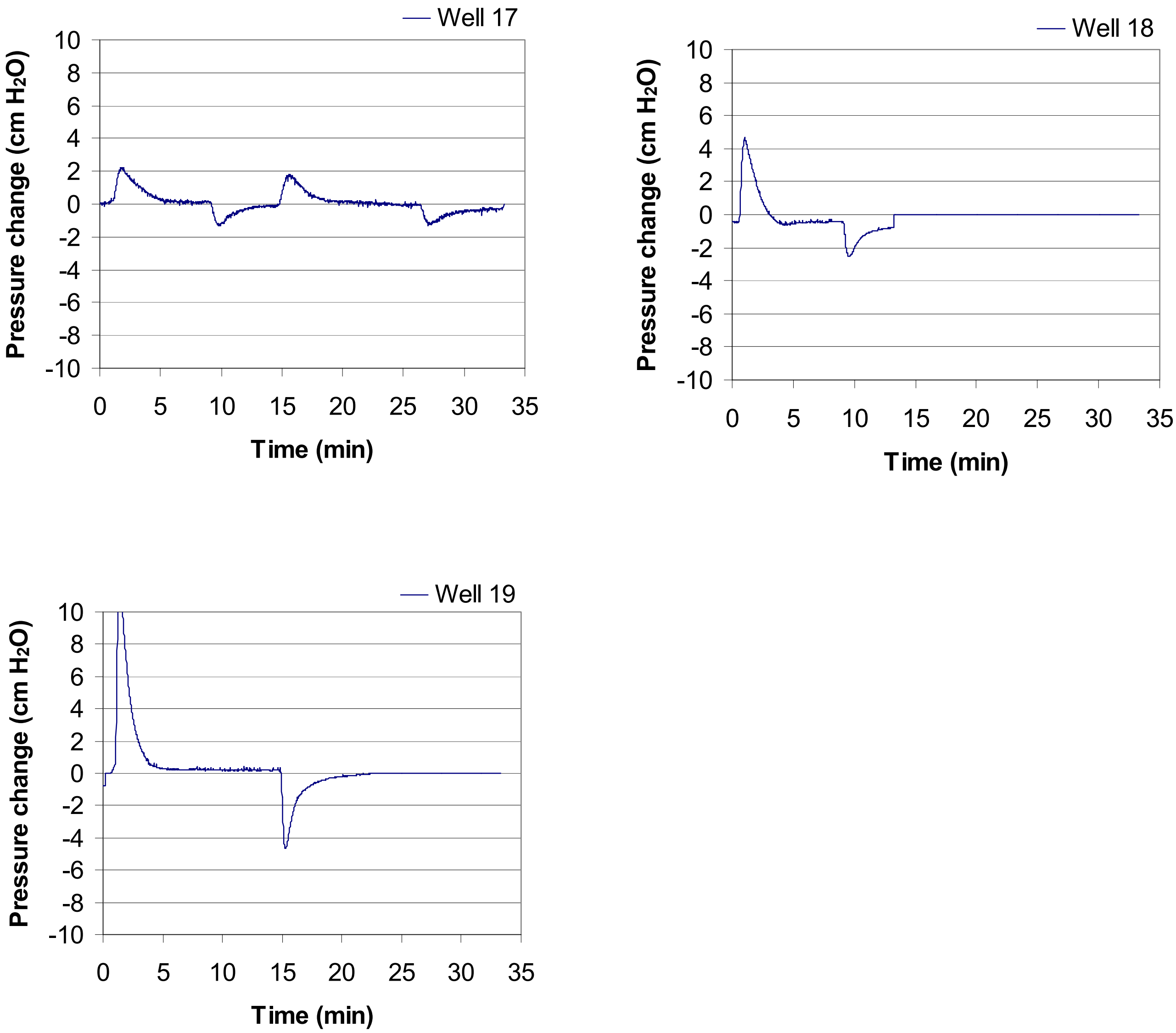



**Figure 5-15. Pressure Response in MW249 versus Time during Injection into Sparge Well 17, 18, and 19 Fairchild AFB, WA**

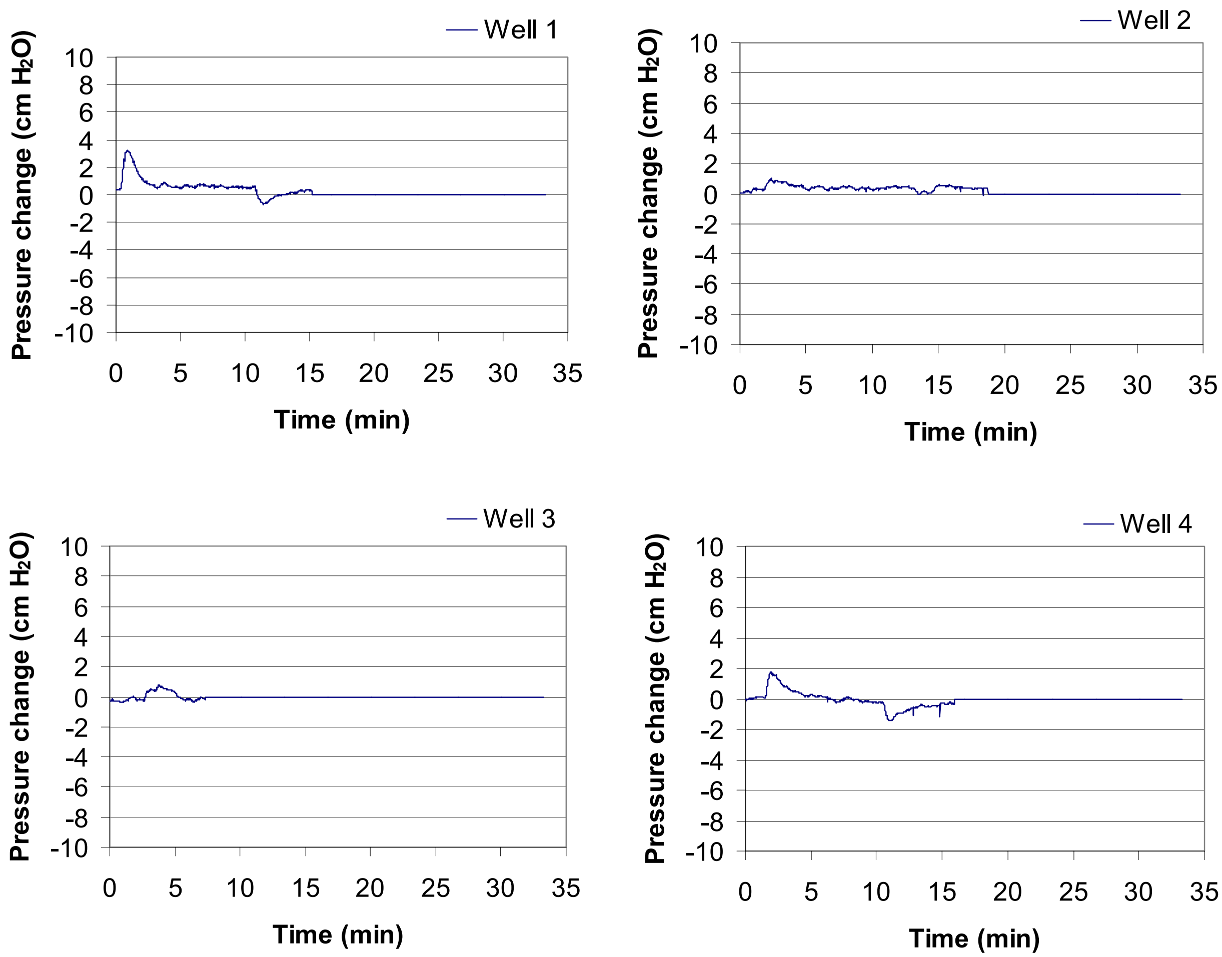



**Figure 5-16. Pressure Response in MW250 versus Time during Injection into Sparge Well 1, 2, 3, and 4, Fairchild AFB, WA**

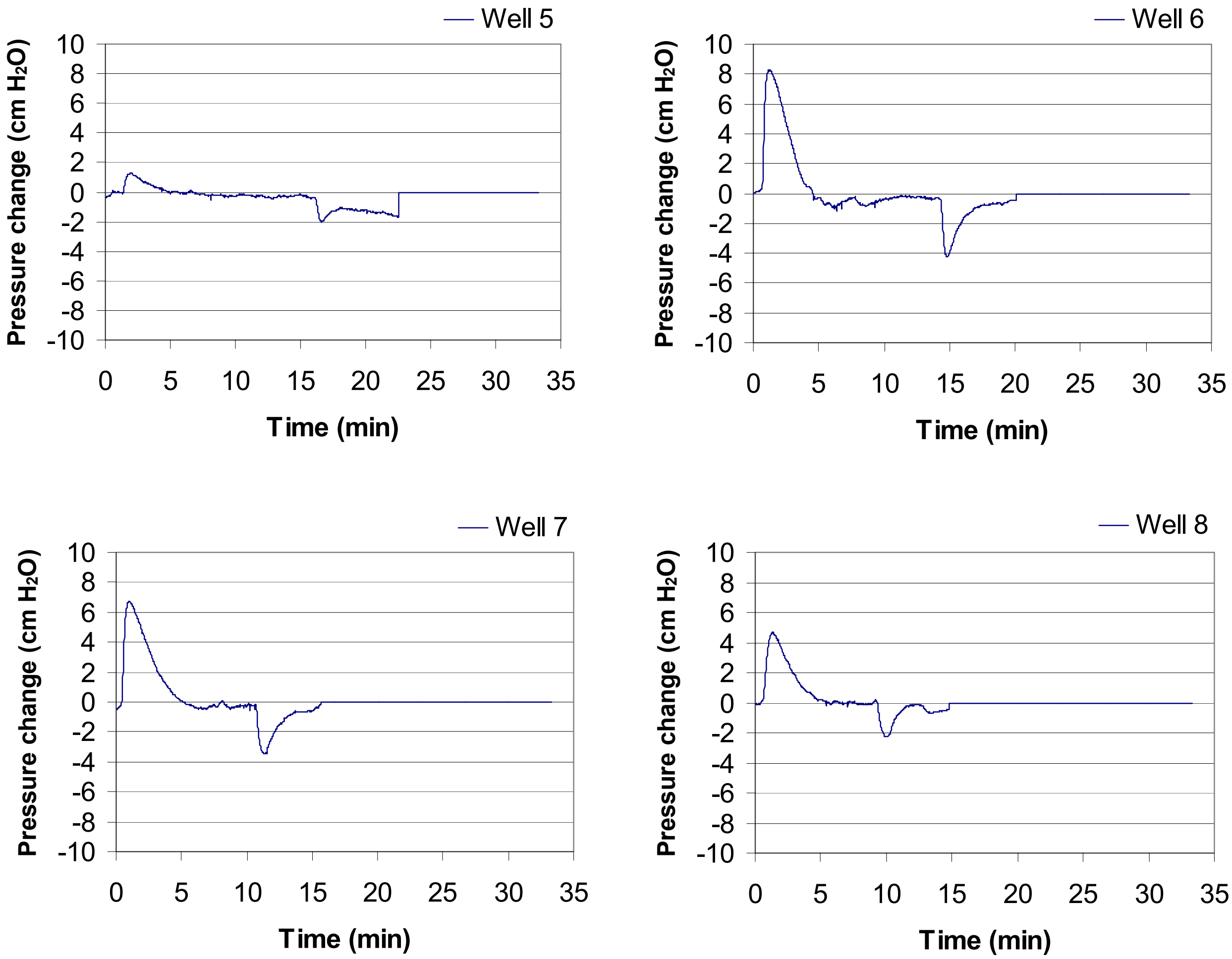



**Figure 5-17. Pressure Response in MW250 versus Time during Injection into Sparge Well 5, 6, 7, and 8, Fairchild AFB, WA**

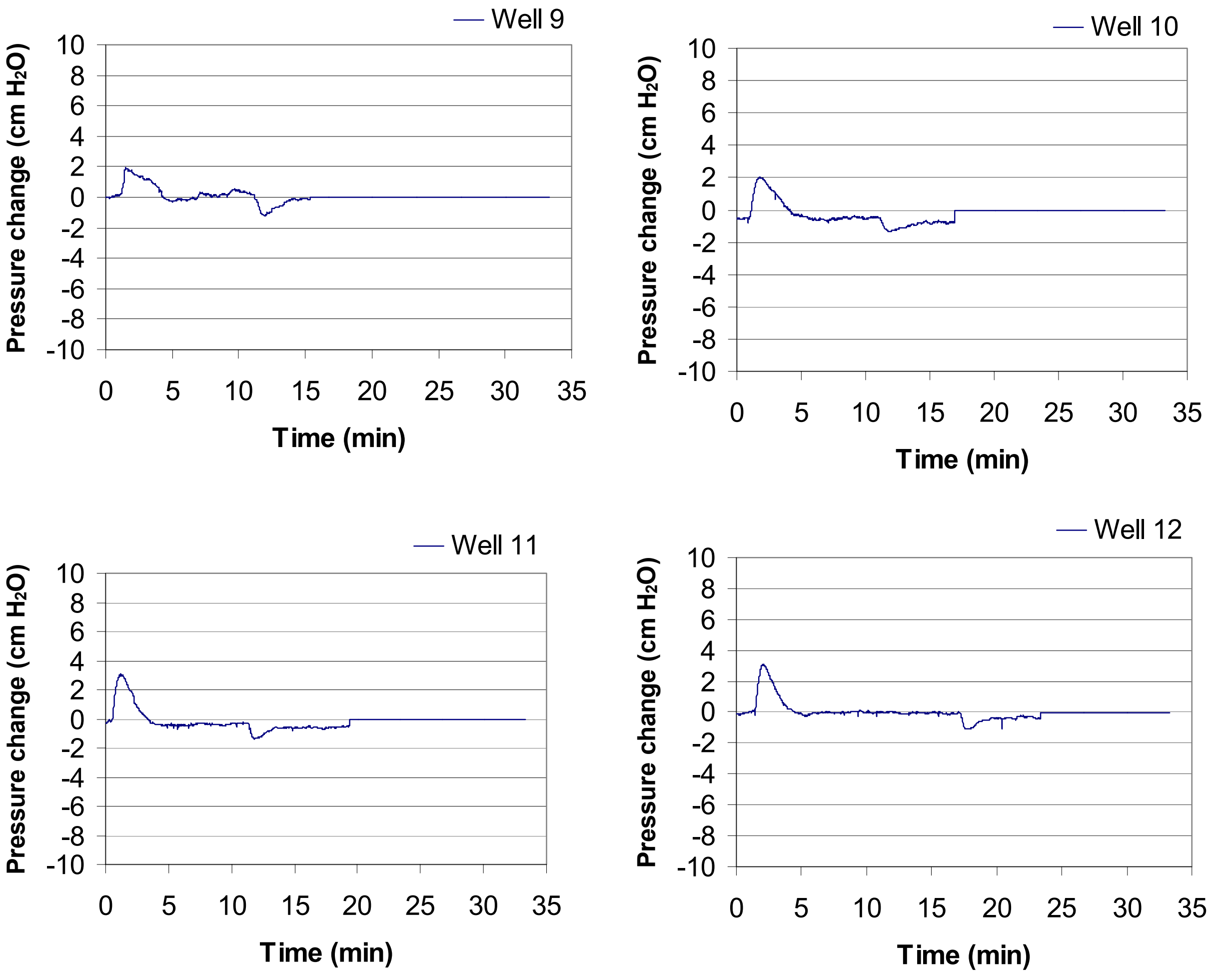



**Figure 5-18. Pressure Response in MW250 versus Time during Injection into Sparge Well 9, 10, 11, and 12, Fairchild AFB, WA**

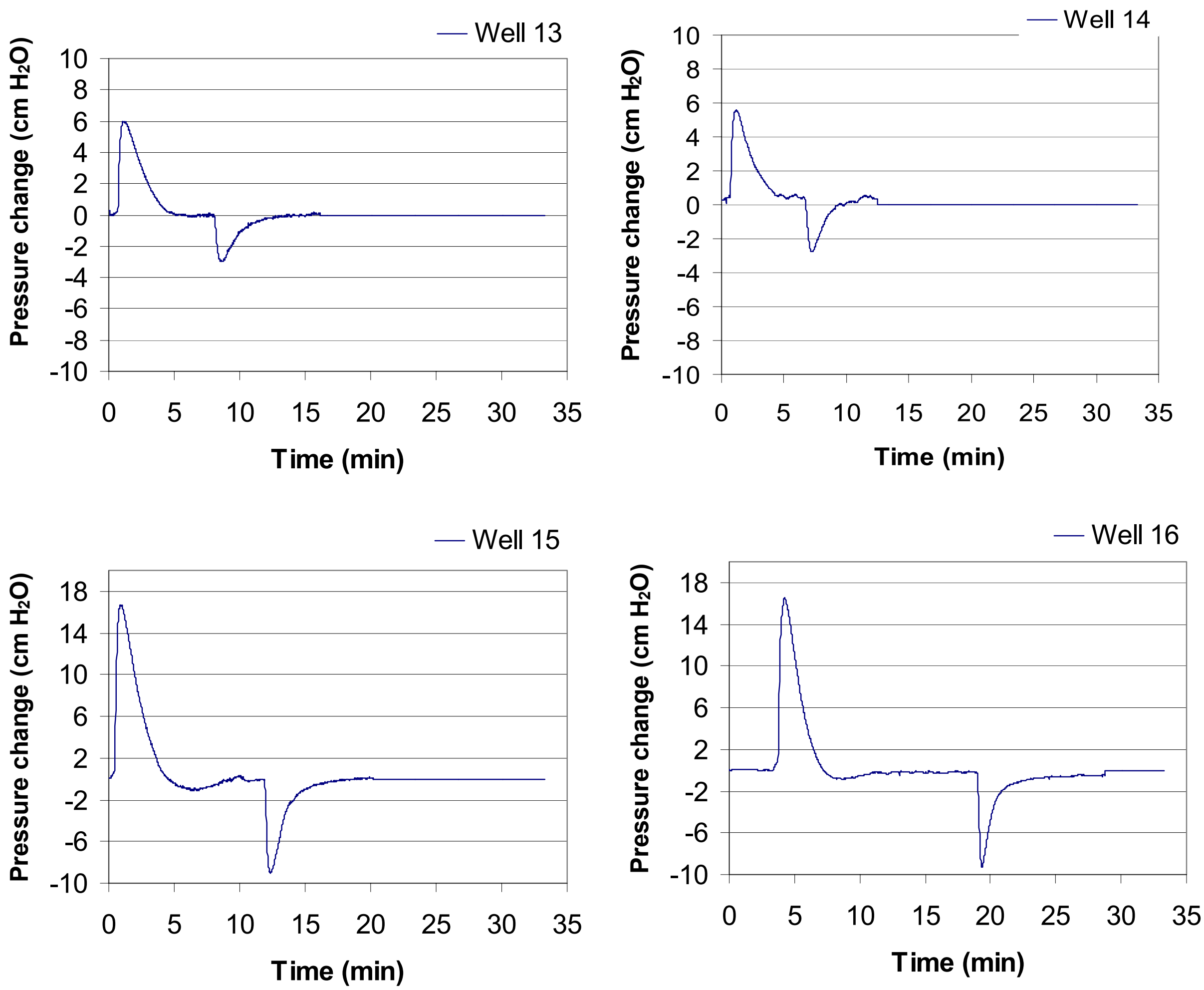



**Figure 5-19. Pressure Response in MW250 versus Time during Injection into Sparge Well 13, 14, 15, and 16, Fairchild AFB, WA**

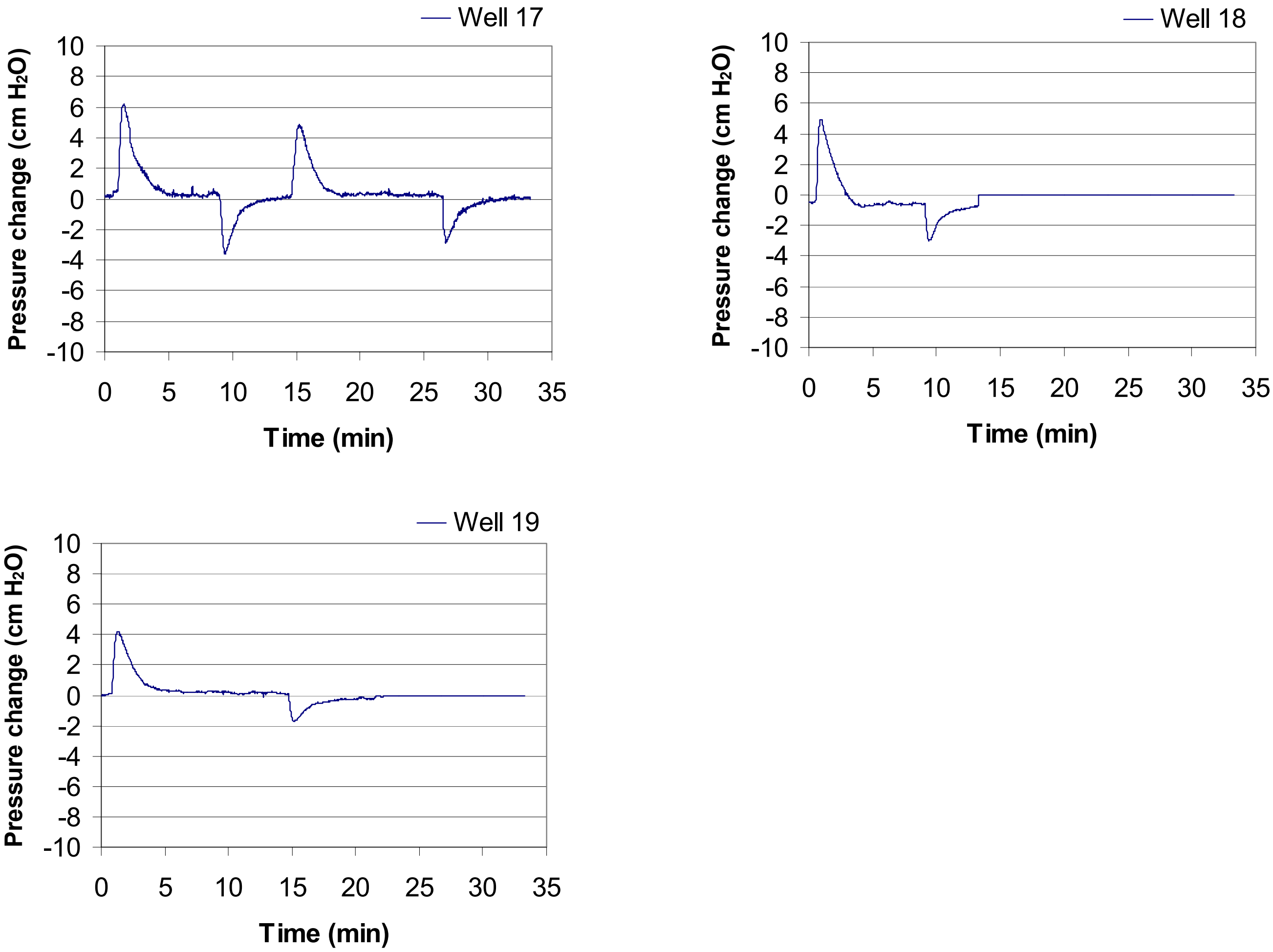



**Figure 5-20. Pressure Response in MW250 versus Time during Injection into Sparge Well 17, 18, and 19, Fairchild AFB, WA**

2. The wells should be installed with direct-reading flow meters for each well. This would allow for monitoring of flow into individual wells to ensure that the system is functioning as expected.

## 5.3 Landfill 4, Fort Lewis, WA

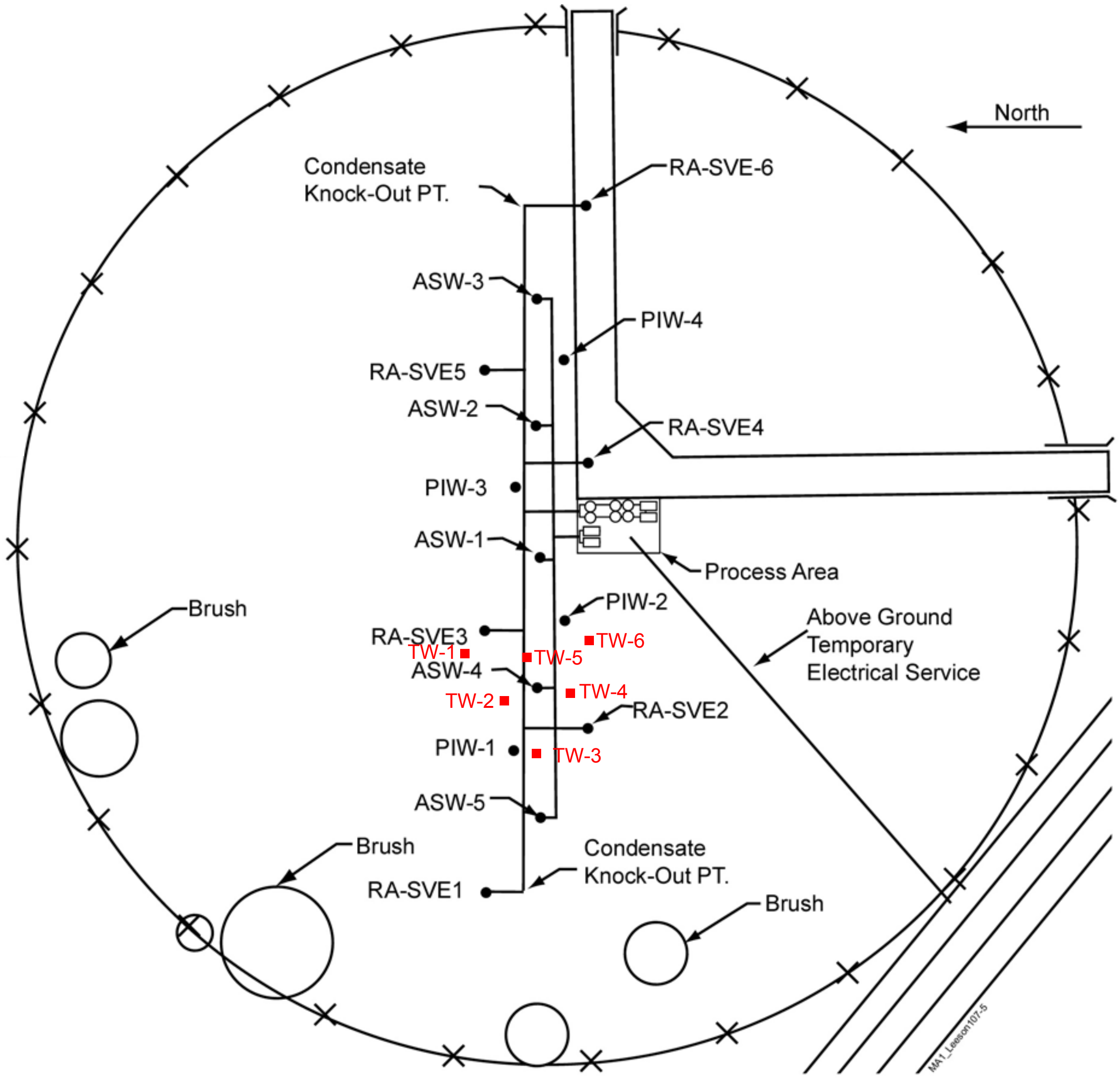
**5.3.1 Site Information.** The remedial system currently in place at LF4 is an air sparging/soil vapor extraction system located just south of the Northeast landfill cell (Figure 3-5). In order to conduct system testing, six test wells were installed at Landfill 4 as part of this study. The test wells were installed in two concentric circles around air injection well ASW-4. Total borehole depths ranged from 35 to 40 ft bgs. Each well was completed with 1 ft of 2-inch diameter 20-slot screen and schedule 40 PVC casing. The annular space was backfilled with silica sand to approximately 1 ft above the top of the screen. Bentonite chips were then added until the static water level was below the top of the bentonite. A soil-gas monitoring point was then installed in the borehole within a 2-ft interval of silica sand. Bentonite chips were then added up to 2 ft bgs. The borehole was then sealed to the surface with grout. A diagram of the system showing installations by the MAS team is shown in Figure 5-21.

**5.3.2 Results.** Two series of tests were conducted at this site to evaluate the existing air sparging system and to validate the Air Sparging Design Paradigm. The first series of tests were conducted at an injection flowrate of 20 to 25 scfm into air sparge well 4 (ASW-4) and at an extraction rate of 400 scfm. Tests conducted at these flowrates included: a) pressure transducer responses; b) $SF_6$ tracer testing; and c) helium tracer testing. A push-pull test was attempted, but residual dissolved oxygen concentrations and permeability were too high. A second set of tests was conducted with an injection rate of approximately 70 scfm into ASW-4. Diagnostic testing at this flowrate included groundwater pressure testing and an $SF_6$ tracer test.

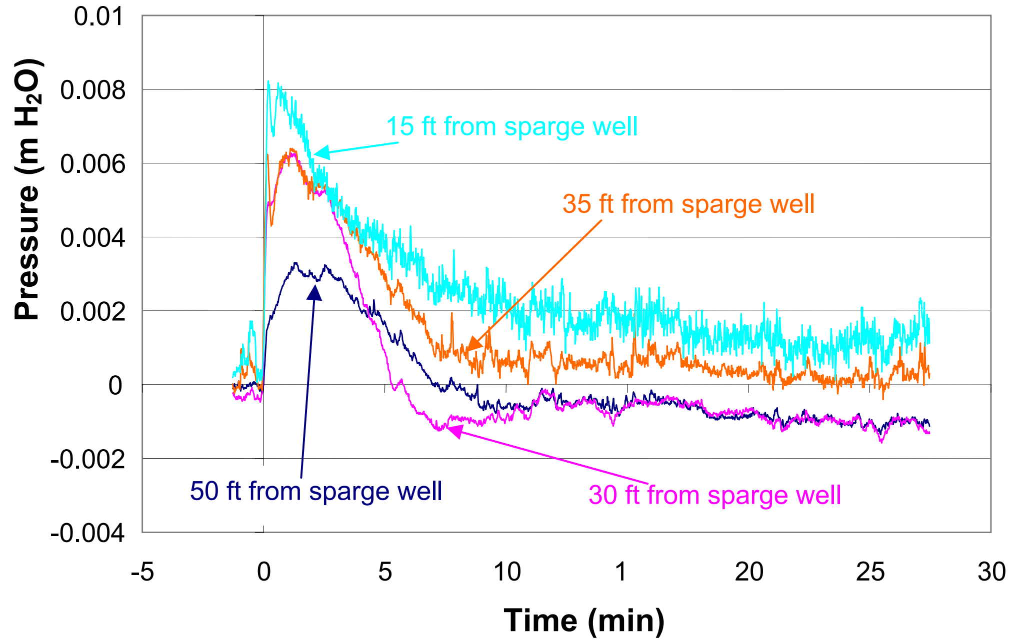
At the low injection rate, groundwater pressure changes at startup and shutdown were too small to be measured. Even at the 70-scfm injection rate, pressure testing indicated a very small response (<0.01 m $H_2O$) indicating that the permeability was very high. At the high flowrate the pressure increased rapidly and quickly dropped back to hydrostatic levels (Figure 5-22), indicating that there is little stratification in the region of the injection well to cause air to be trapped in the subsurface.

An $SF_6$ tracer test conducted at the low injection rate confirmed that the zone of influence around the well was small, with the majority of the $SF_6$ found within a radius of 10 ft from the injection well (Figure 5-23). A similar test at the high flowrate showed similar results.

**5.3.3 Summary and Conclusions.** The existing system has sparge wells installed on 50-ft spacings. Based on the results from this study, the design approach of 15-ft well spacings recommended in the Air Sparging Design Paradigm would be better suited to the site and result in


North
Condensate
Knock-Out PT.
RA-SVE-6
ASW-3
PIW-4
RA-SVE5
ASW-2
RA-SVE4
PIW-3
ASW-1
Process Area
PIW-2
Brush
RA-SVE3
TW-1
TW-5
TW-6
ASW-4
TW-4
TW-2
RA-SVE2
Above Ground
Temporary
Electrical Service
PIW-1
TW-3
ASW-5
Brush
Condensate
Knock-Out PT.
RA-SVE1
Brush

A)




B)

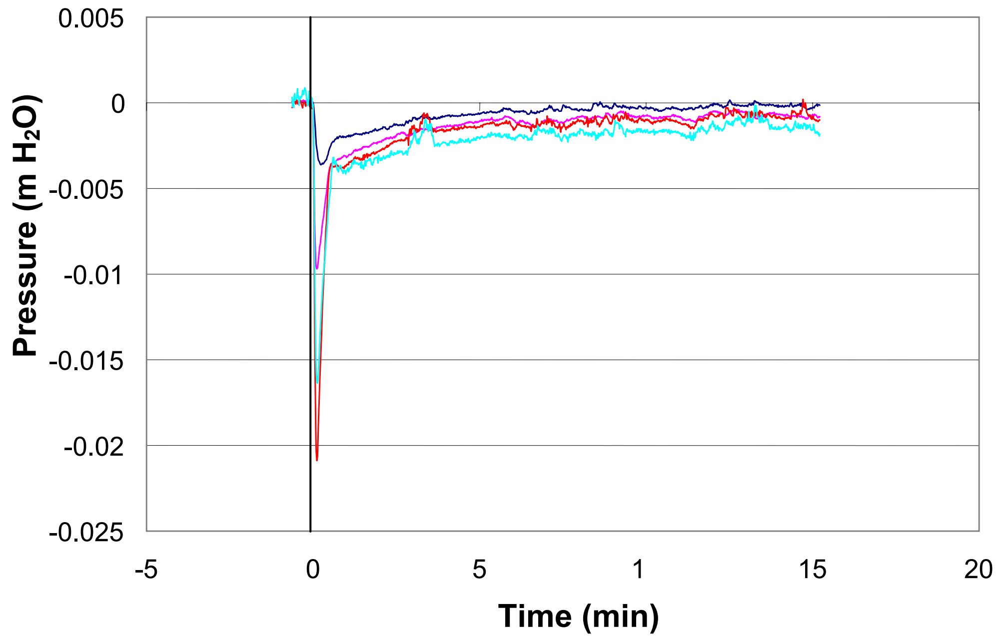



**Figure 5-22. Pressure Response versus Time During (A) Start-Up and (B) Shutdown of Air Injection at the High Air Flowrate, Fort Lewis, WA**

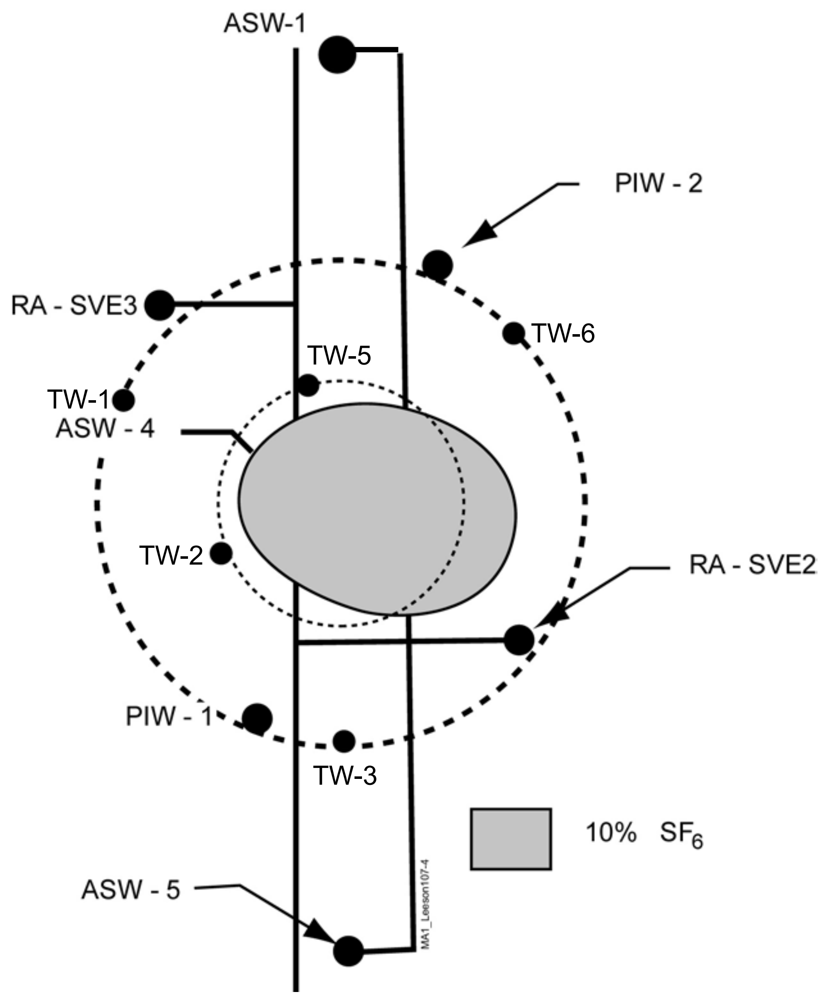



**Figure 5-23. $SF_6$ Distribution in Groundwater during the $SF_6$ Tracer Test, Fort Lewis, WA**

more successful treatment. In addition, an air injection rate of 20 scfm per well would be sufficient to achieve site treatment. The lower air flowrates would result in lower capital and operational costs associated with air injection and extraction equipment.

As the air sparging system is designed now, complete treatment of the contaminated plume cannot be attained. The soil at the site is so permeable that a large zone of influence is not possible. In order to achieve more complete coverage of the contaminated aquifer, installation of additional air sparging wells would be necessary. Fortunately, the air injection compressor currently in place is likely to have the capacity to accommodate injection into more wells at a lower flowrate per well.

## 5.4 Cape Canaveral Air Station, FL

**5.4.1 Site Information.** As discussed previously, a horizontal air sparging system was installed to intercept and treat the VC plume in groundwater to prevent the release of contaminants downgradient of the site. The overall objective of the horizontal air sparging system at Site FT-17 was to reduce VC concentrations to below 50 µg/L in groundwater, thereby reducing the concentration of VC in the adjacent drainage canal to below 1 µg/L.

The MAS team installed four wells (by direct push) for pressure transducer measurements (PTW-1, 2, 3, and 4) constructed of 1-inch diameter schedule 40 PVC casing and 10-slot screen. PTW-1 and PTW-3 are screened from 13 to 15 ft bgs, while PTW-2 and PTW-4 are screened from 12.5 to 15 ft bgs. Holes were drilled into the caps on the well risers to allow pressure created by the air sparging system to dissipate instead of blowing the caps off the wells or pushing the casings out of the ground. Direct push implants were also installed at eight locations for sampling groundwater and soil gas. The implant screens were placed at 3, 6, 10, and 14 ft bgs at each of the locations. A site diagram illustrating these new installations is shown in Figure 5-24.

The existing air sparging system utilized six horizontal wells, each approximately 200 ft long. Testing conducted as part of this demonstration focused on one leg of the sparging system, horizontal well number 4. Total flow into the well was approximately 50 scfm. Previously collected performance data was limited to upgradient and bayou concentrations of chlorinated compounds. To the author's knowledge, no diagnostic tests had ever been done on system prior to the arrival of the Multi-Site Air Sparging team.

**5.4.2 Results.** The diagnostic tests conducted at this site included: a) pressure transducer measurements; b) $SF_6$ in groundwater tracer test; and c) vadose zone helium tracer test.

Visual inspection showed that air had reached the "tail end" of sparge well 4. This implied that the injected air was flowing out over the entire length of the horizontal well. Visual observations also indicated that the air was likely stratified below a confining unit located at 5 to 10 ft below ground surface. Visual observations that supported this are:

- Geysers in the deeper well completions and artesian Geoprobe sampling points.
- Bubbles coming up from the floor of the bayou located 20 to 50 ft away from the well.
- When the air injection system was turned off, bubbles continued showing up in the bayou for several hours.

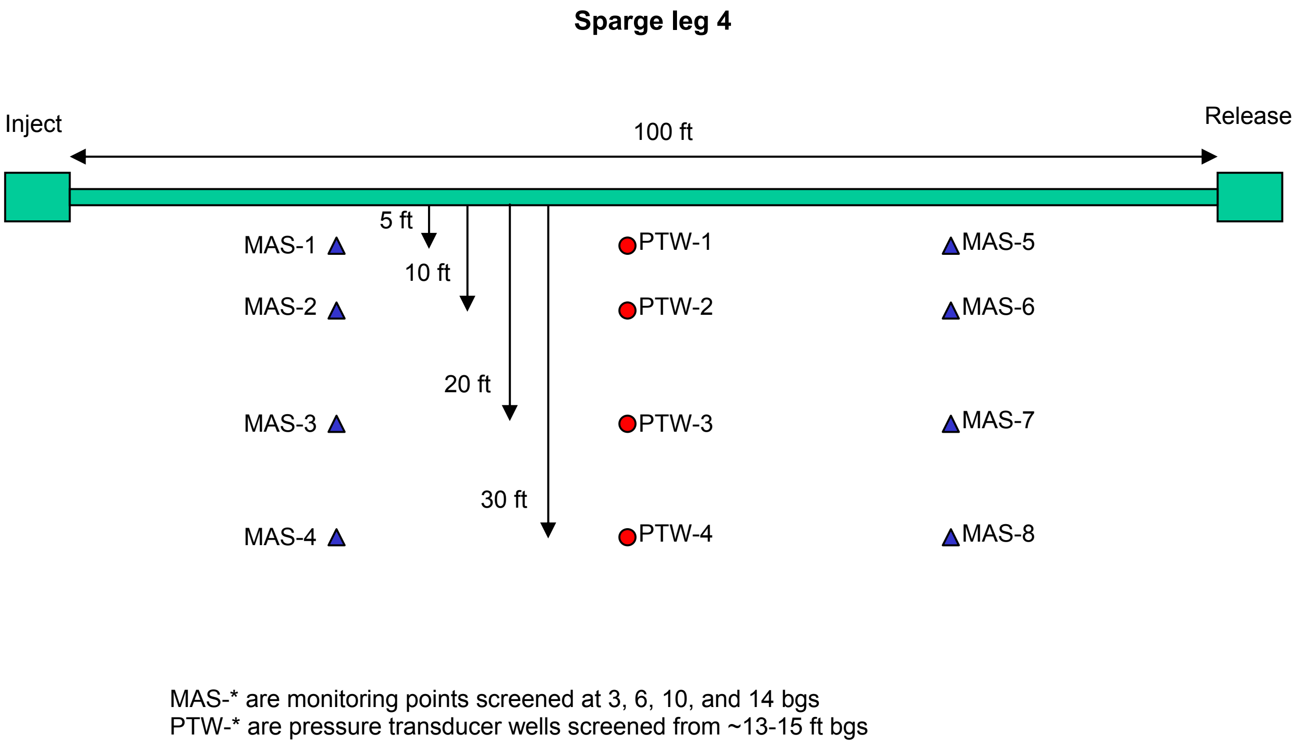



**Figure 5-24. Site Map Showing Equipment Installed by the MAS Team, Cape Canaveral AS, FL**

Pressure measurements during system startup (Figure 5-25) support the idea that air was being stratigraphically trapped below the water table, because after approximately 5 hours, the pressure was still substantially elevated above the hydrostatic level.

The distribution of $SF_6$ in the groundwater around sparge well 4 after 12 hours of sparging is shown in Table 5-1. The data suggest that sparge air is spreading throughout the vicinity of the sparge well.

To assess air distribution during air sparging at the site, helium was added to the sparge air and measured in the vadose zone shortly after introduction. Table 5-2 lists measured concentrations at a number of locations around the sparge well. The widespread appearance of helium suggests that even though the air is stratigraphically trapped, a significant amount of the sparge air is finding its way up through the saturated zone throughout the treatment area. The helium concentration in the injection air ranged from 0.57 to 0.83% by volume.

At the Cape Canaveral NAS oxygen transfer rates were assessed using the $SF_6$ delivery method described by Bruce et al. (2001). The conservative tracer $SF_6$ was metered into the injection gas

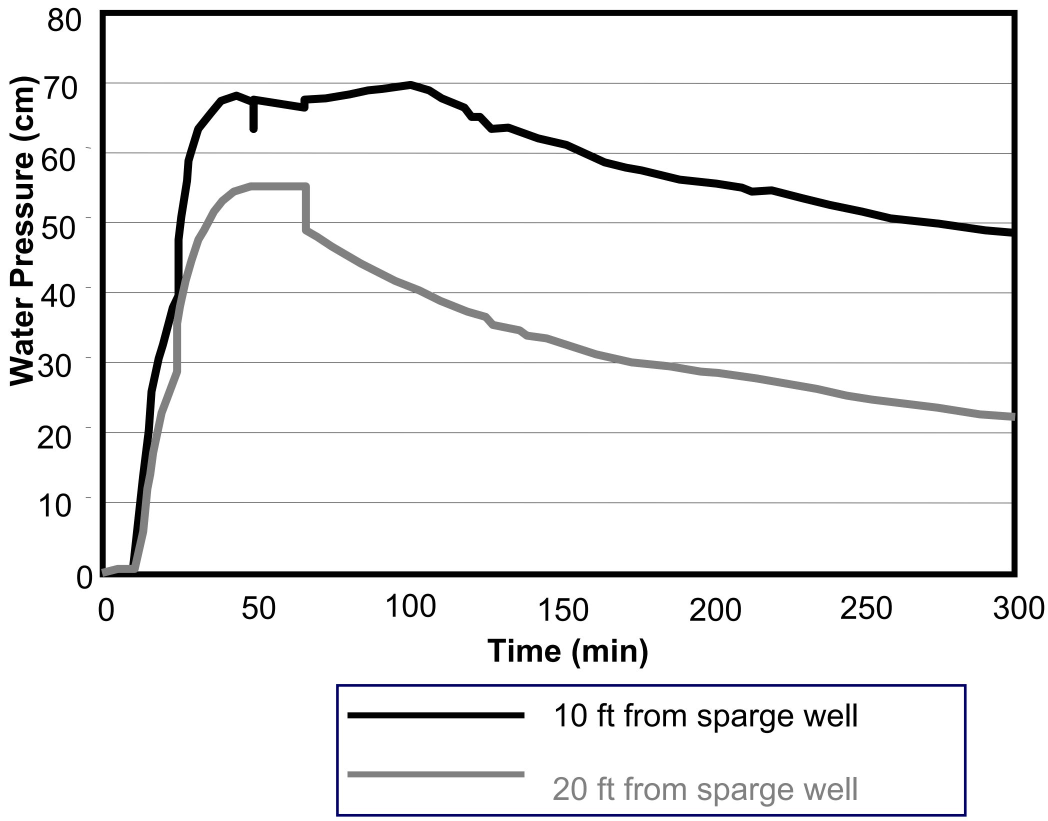



**Figure 5-25. Pressure Testing in Horizontal Well 4, Cape Canaveral AS, FL**

**Table 5-1. Distribution of SF6 in Groundwater After Air Injection into Sparge Well 4, Cape Canaveral AS**

| Sample | % Saturation with respect to $SF_6$ concentration in injected air |
|---|---|
| Sparged water | 100 |
| MW2-6 | 79 |
| MW3-6 | 78 |
| MW4-6 | 16 |
| MW4-10 | 118 |
| MW3-10 | 93 |
| MW1-6 | 122 |
| MW4-14 | 136 |
| MW2-14 | 126 |
| MW5-6 | 12 |
| MW6-6 | 7 |
| MW8-6 | 3 |
| MW7-6 | 65 |
| MW1-14 | 121 |
| MW3-14 | 113 |
| MW8-14 | 5 |
| MW8-10 | 69 |
| MW7-14 | 21 |
| MW5-10 | 95 |
| MW5-14 | 101 |

**Table 5-2. Helium Appearance at Monitoring Points During the Helium Tracer Test, Cape Canaveral AS, FL**

| Location | % Helium |
|---|---|
| MW1-3 | 0.23 |
| MW1-10 | 0.4 |
| MW2-3 | 0.12 |
| MW2-10 | 0.4 |
| MW3-3 | 0.09 |
| MW3-10 | 0.18 |
| MW4-3 | 0.14 |
| MW4-10 | 0.04 |
| MW5-3 | 0.21 |
| MW5-10 | 0.29 |
| MW6-3 | 0 |
| MW6-10 | 0 |
| MW7-10 | 0.09 |
| MW8-3 | 0 |
| MW8-10 | 0 |

stream and its appearance in groundwater was monitored after 4 and 12 hours. Oxygen transfer rates were then calculated from the dissolved $SF_6$ concentrations, and the results are presented below in Table 5-3.

As can be seen, the assessed oxygen mass transfer rates ranged between 1 to 150 mg-$O_2$/L-$H_2O$/d (approximately). This range is comparable to values observed at other sites using similar methods. In many cases the 4-hour average rates are higher than the 12-hour average rates, suggesting that equilibrium between the air channels and groundwater was occurring in less than a 12-h time period. Thus, the actual potential oxygen transfer rates could be as much as two to three times larger than the 12-hour average values given above. Thus, at many of the monitoring locations it is likely that oxygen transfer rates could be as high as approximately 150 mg-$O_2$/L-$H_2O$/d. This value is comparable to the maximum value observed at other sites under similar test conditions.

**5.4.3 Summary and Conclusions.** These results demonstrated that the horizontal well that was examined is functioning properly, with flow along the entire length of the well. Horizontal wells often have problems with severe short-circuiting of air and are often ineffective at delivering air to the target treatment zone. The diagnostic tests implemented here demonstrate that this is not the case

**Table 5-3. Oxygen Transfer Rates Calculated from $SF_6$ Tracer Appearance, Cape Canaveral AS**

| Sample | % Saturation with respect to $SF_6$ concentration in injected air |
|---|---|
| MW2-6 | 30.4 |
| MW2-6[1] | 143.6 |
| MW3-6 | 30.2 |
| MW3-6[1] | 52.0 |
| MW4-6 | 6.2 |
| MW4-6[1] | 21.8 |
| MW4-10 | 45.5 |
| MW3-10 | 35.7 |
| MW1-6 | 46.9 |
| MW1-6[1] | 124.4 |
| MW4-14 | 52.4 |
| MW2-14 | 48.5 |
| MW5-6 | 4.6 |
| MW5-6[1] | 11.7 |
| MW6-6 | 2.6 |
| MW6-6[1] | 2.1 |
| MW8-6 | 1.0 |
| MW7-6 | 24.9 |
| MW7-6[1] | 87.8 |
| MW1-14 | 46.4 |
| MW3-14 | 43.6 |
| MW8-14 | 2.0 |
| MW8-10 | 26.6 |
| MW7-14 | 8.1 |
| MW5-10 | 36.7 |
| MW5-14 | 39.0 |

[1]4-hour test; all other are 12-hour measurements

at this site. However, it should be emphasized here that the costs associated with installing horizontal wells is significant and vertical wells often can deliver air to the target treatment zone for much less cost and with less risk of short-circuiting of air.

Results from this diagnostic testing also demonstrated that the pressure and helium tracer testing provided good indications of air distribution, as confirmed by $SF_6$ tracer testing. These results emphasized the robustness of the pilot test as prescribed in the Air Sparging Design Paradigm.

## 5.5 DoDHF Novato, CA.

**5.5.1 Site Information.** No additional equipment was installed at this site as described in Section 4. Diagnostic testing was conducted using the on-site compressor, operated at a flowrate of 4.2 scfm and a pressure of 15 psi.

**5.5.2 Results.** Activities were conducted at Site 957/970. Previous activities at this site indicated that significant mass removal was achieved through the operation of air sparging and soil vapor extraction systems. An estimated 23,000 lb of gasoline were calculated to have been removed through the soil vapor extraction system. In general, TPH and benzene concentrations in the off-gas stream decreased substantially since system startup. The latest sampling event (October 5, 1999) did reveal a significant TPH removal rate of 50 lb/day calculated based on off-gas concentrations and average system flowrate. This removal rate is much increased over those observed during summer months and likely is associated with the seasonal low water table level at that time of year. Low water table levels result in a larger cross section area available for gas flow as well as exposure of deeper soils that are only above water during low water table events. These deeper soil locations are the least impacted by mass removal, and when exposed can contribute significant TPH to the extracted vapor stream. The SVE system TPH-G removal rate had decreased to about 3 lb/day during periods of higher water table levels earlier in the year. For this reason, it was determined that the recovery potential of the existing system had been met unless extraction would take place only during seasonal low water levels. Additional extraction wells would be required for the system to achieve significant additional hydrocarbon removal throughout the year; however, risk assessment activities indicated that concentrations at the site do not exceed risk-based screening levels based on future site usage. Therefore, the air sparging and SVE systems were shut down in early October 1999.

Groundwater samples were collected from monitoring wells and air sparging wells prior to startup of remedial activities to get baseline concentrations. The initial (pre-remediation) sampling took place in May 1998. Quarterly groundwater monitoring events were conducted in which monitoring wells were sampled, but air sparging wells were not intended for routine plume monitoring, and were not sampled during the quarterly sampling events. Groundwater samples were collected from monitoring and sparge wells again one year later (May 1999) and analyzed to determine the effects of remedial activities on groundwater concentrations. Additional sparge wells were not installed until October 1998; therefore, initial sampling data for these wells is from November 1998, and the corresponding one-year sampling event took place in November 1999. Table 5-2 presents the MTBE and benzene concentrations obtained from the air sparging wells in 1998 and 1999.

Groundwater concentrations in wells located within Area A averaged approximately 99,000 µg/L for MTBE and 6,600 µg/L for benzene in May 1998. After one year of operation, the average concentrations of MTBE and benzene within Area A decreased to approximately 20,000 µg/L and 4,860 µg/L, respectively. This calculates to an average reduction of approximately 80% MTBE and 86% benzene in Area A wells.

Groundwater concentrations in the wells within Area B showed a similar reduction to the wells in Area A, with the exception of AS-3B. The average initial concentrations of MTBE and benzene in wells located within Area B were approximately 58,000 µg/L and 3,000 µg/L, respectively. Following one year of active remediation, the average concentrations of MTBE and benzene were 17,000 µg/L and 230 µg/L, respectively. Within Area B (excluding AS-3B), the average concentrations of MTBE and benzene decreased by 70% and 92%, respectively, after one year of system operation. Groundwater monitoring results obtained from adjacent monitoring wells, 970 MW-4 and MW-5B, confirm the reduction in concentration of MTBE and benzene. Although the MTBE concentration has increased slightly in AS-3B, the benzene concentration decreased by more than 90% over the same period.

Groundwater monitoring results from Area DE do not exhibit a clear pattern in reduction of MTBE concentrations; however, benzene concentrations in all Area DE wells have decreased by approximately 90% after one year of system operation. The average initial concentrations of MTBE and benzene within Area DE were approximately 28,000 µg/L and 590 µg/L, respectively. After one year of operation, the average concentrations of MTBE and benzene within Area DE were approximately 20,000 µg/L and 70 µg/L, respectively. MTBE concentrations within the initially installed sparge wells in Area D (AS-1D and AS-2D) were seen to increase after one year of operation; however a significant reduction in benzene was observed in those wells during the same time period. On the contrary, a reduction in MTBE concentrations in system expansion sparge wells was observed after one year of operation. On average, a greater than 90% reduction in MTBE and benzene concentrations was observed in system expansion sparge wells in Area DE from 1998 to 1999.

To the author's knowledge, no previous diagnostic testing had been conducted at this site to determine air distribution around the injections wells. The SVE system at the site had been removed and there were few monitoring wells and vadose zone monitoring points. As a result, the only test conducted by the Multi-Site Air Sparging team was a to measure pressure response. Using the on site compressor, injection well AS3D was sparged at a flowrate of approximately 4.2 scfm and a pressure of 15 psi. The groundwater pressure response to system startup and shutdown was measured in monitoring wells MW6 (9.75 m southwest of AS3D) and MW7 (2.75 m north of AS3D).

**Table 5-4. MTBE and Benzene Concentration in Sparge Wells – Initial and Following One Year of Operation, DoDHF, Novato, CA**

| Well ID | MTBE Concentration (μg/L) | | Benzene Concentration (μg/L) | |
|---|---|---|---|---|
| | Initial (1998) | One year (1999) | Initial (1998) | One year (1999) |
| AS-1A[1] | 280,000 | 23,000 | 13,000 | 4,200 |
| AS-2A[1] | 26,000 | 11,000 | 2,000 | 52 |
| AS-3A[1] | 85,000 | 4,500 | 5,300 | 390 |
| AS-4A[2] | 36,000 | 83 | <500 | <0.5 |
| AS-5A[2] | 37,000 | 920 | <500 | 6.1 |
| AS-6A[2] | 130,000 | 82,000 | 18,000 | <500 |
| AS-1B[1] | 46,000 | 24,000 | 4,700 | 970 |
| AS-2B[1] | 220 | 55 | 110 | 7.5 |
| AS-3B[1] | 53,000 | 64,000 | 4,500 | 23 |
| AS-4B[2] | 25,000 | 1,800 | 3,100 | 13 |
| AS-5B[2] | 95,000 | 5,100 | 3,400 | 300 |
| AS-6B[2] | 130,000 | 6,900 | 1,900 | <50 |
| AS-1D[1] | 19,000 | 36,000 | 2,000 | 96 |
| AS-2D[1] | 26 | 29 | 46 | 22 |
| AS-3D[2] | 63,000 | 29,000 | 500 | 6,250 |
| AS-4D[2] | 52,000 | 3,200 | 430 | 1.1 |
| AS-1E[1] | 5,900 | 3,800 | 290 | 31 |
| AS-2E[1] | 31,000 | 46,000 | <250 | <20 |

[1]Original system sparge well – sampled in May 2998 and May 1999.
[2]System expansion sparge well – sampled in October 1998 and October 1999.

Pressure results from system startup and shutdown are shown in Figures 5-26 and 5-27. The pressure responses in both wells remained above hydrostatic for the duration of the test (approximately 3 hours). The pressure data suggest that stratigraphic trapping of air below the water table is important at the site. This is supported by the general conceptual model of the geology of the site. Because the testing conducted at the site was limited, it is not possible to assess the effectiveness of air sparging at the site, however, previous experience would suggest that the pressure data is a "red flag" and any future sparging activities should be contingent on a more complete suite of diagnostic tests.

**5.5.3 Summary and Conclusions.** Monitoring at this site was conducted with traditional groundwater monitoring wells and by sampling the injection wells themselves at the end of testing. The system was recently shutdown and it is recommended that the site continue to be monitored for at least a one-year period to ensure contaminant levels do not rebound. System monitoring with

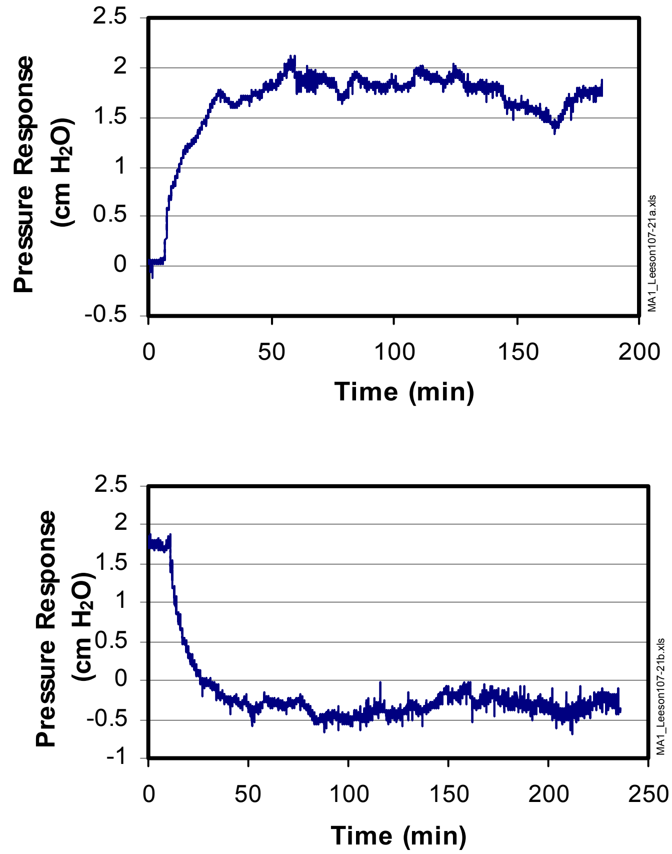
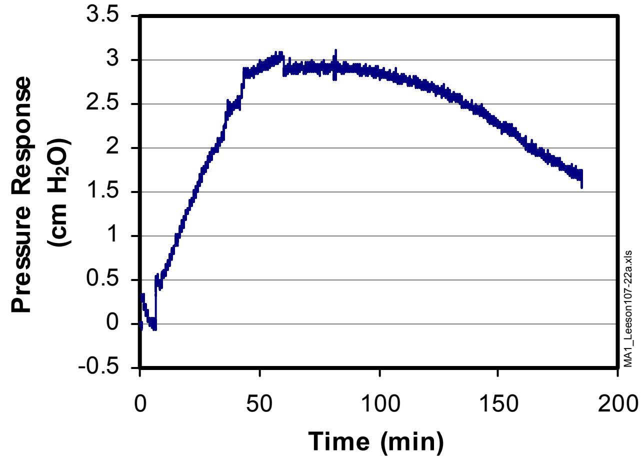



**Figure 5-26. Pressure Response at Monitoring Well MW6, DoDHF Novato, CA**



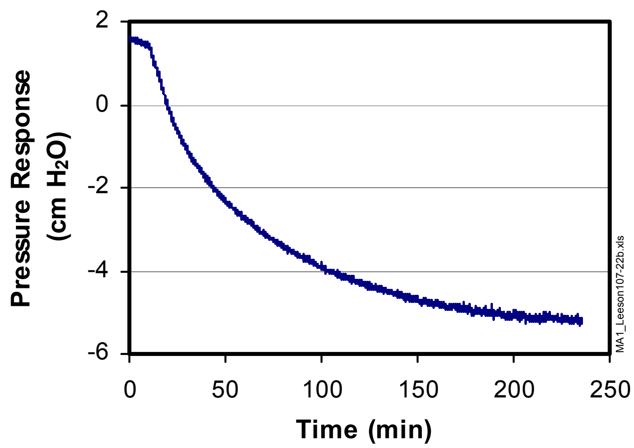




**Figure 5-27. Pressure Response at Monitoring Well MW7, DoDHF Novato, CA**

traditional groundwater monitoring wells and particularly air sparge wells can be problematic (Leeson et al., 2002) and may not provide a representative picture of contaminant removal throughout the aquifer. In particular, the pressure response test indicates that there may be significant quantities of air trapped in the aquifer during injection, and therefore, air may not be reaching the target treatment zone.

## 5.6 MCAS Fuel Farm, Camp Pendleton, CA

**5.6.1 Site Information.** The air sparging system at the MCAS Fuel Farm consists of 15 sparge wells and five soil gas and groundwater monitoring points. Sparge wells were installed to treat areas with the highest contaminant concentrations. The system flowrate is 10 scfm per well operated

intermittently in banks of five wells. Operation of the full-scale air sparging/SVE system began in October 1999 and is currently operating. No additional equipment was installed by the MAS team.

**5.6.2 Results.** Previous diagnostic testing conducted at the site consisted of dissolved oxygen monitoring and measurement of water table changes during injection. Dissolved oxygen measurements were inconclusive, although water table measurements showed a relatively rapid equilibrium to hydrostatic levels. The Multi-Site Air Sparging team conducted additional diagnostic testing at the site, including a helium tracer and a pressure response test.

One set of five sparge wells (SW-1, -2, -3, -7, and -15) with the best collection of monitoring devices was selected for testing. The entire set was turned off/on to measure pressure. Pressure response was monitored in wells MW12R and MW-02. Helium tests were conducted by adding helium into one sparge well line in the manifold and monitoring helium appearance in monitoring points MP-1, MP-2, and MP-3 at a depth of 5 ft bgs.

Pressure response curves are shown in Figures 5-28 and 5-29. Figures 5-28 and 5-29 represent the pressure response curves obtained from monitoring well MW-02 and MW12r, respectively. Results from both monitoring wells suggest that there are stratigraphic layers trapping air in the aquifer. However, helium tracer data show that the injected air is reaching the vadose zone within a zone of influence of approximately 12 ft (Table 5-5). Little to no helium was detected in monitoring point MP2 during tests 1, 3, and 4, which is located approximately 18 ft from SW-1. It is not surprising, therefore, that during tests 2 and 5, little to no helium was detected in any of the monitoring points, the closest of which was located approximately 15 ft from the injection well.

**5.6.3 Summary and Conclusions.** These results demonstrate the importance of multiple lines of evidence when evaluating air sparging systems. Based on the pressure testing alone, or combined with the previous results of dissolved oxygen testing, it may have been concluded that air sparging was infeasible at this site. However, deep vadose zone helium tracer testing demonstrated that injected air was reaching the vadose zone within a small zone of influence around the well.

Injected air appears to reach the vadose zone within approximately 10 ft from the injection well. Well spacings at this site are greater than the 15-ft well spacing guidance in the Air Sparging Design Paradigm; however, the treatment goal here was designed to treat “hot spots”; therefore, the selected spacing may be adequate for this design goal.

**Table 5-5. Description of Helium Tracer Data for Camp Pendleton**

| Test Number | Sparge Well (s) on | He injection well | Monitoring point | % Saturation at monitoring point |
|---|---|---|---|---|
| 1 | 1,2,3,15,7 | SW1 | MP1 | 98 |
| | | | MP2 | 0 |
| | | | MP3 | 100 |
| 2 | 1,2,3,15,7 | SW3 | MP1 | 5 |
| | | | MP2 | 3 |
| | | | MP3 | 5 |
| 3 | 1,2,3,15,7 | SW1 | MP1 | 83 |
| | | | MP2 | 3 |
| | | | MP3 | 89 |
| 4 | 1 | SW1 | MP1 | 90, |
| | | | MP2 | 4 |
| | | | MP3 | 97 |
| 5 | 15 | SW15 | MP1 | 0 |
| | | | MP2 | 9 |
| | | | MP3 | 1 |

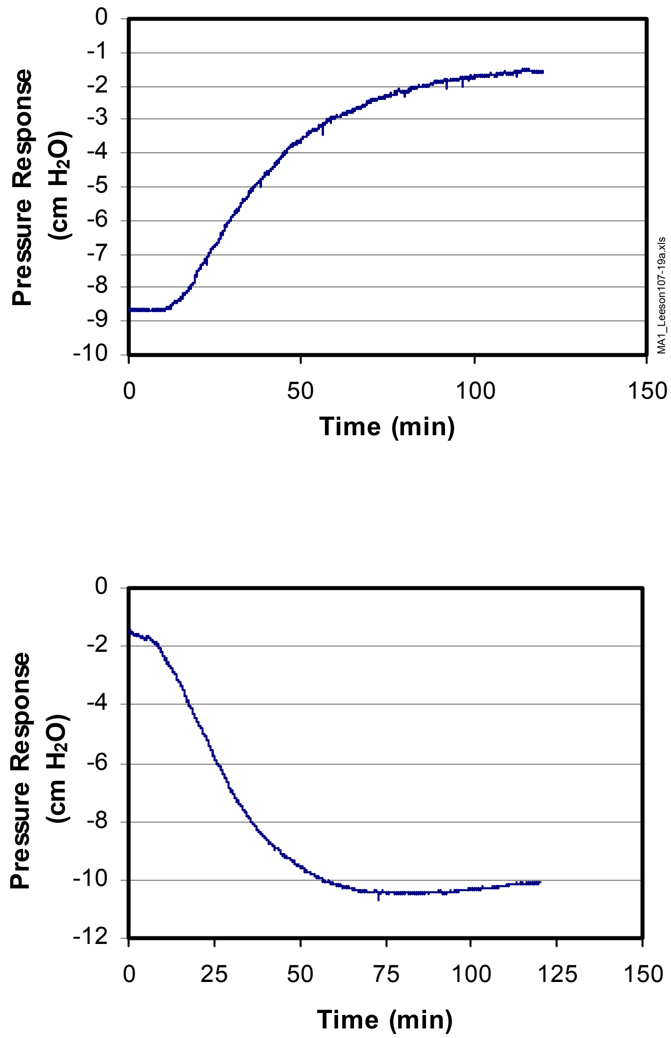
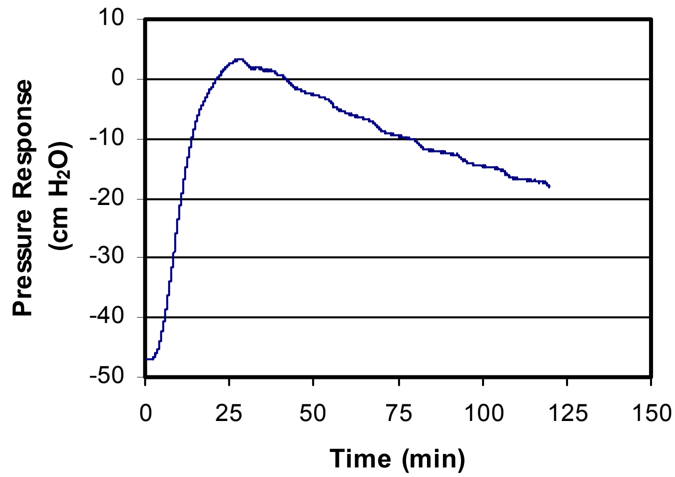



**Figure 5-28. Pressure Response at Monitoring Well MW-02, Camp Pendleton, CA**



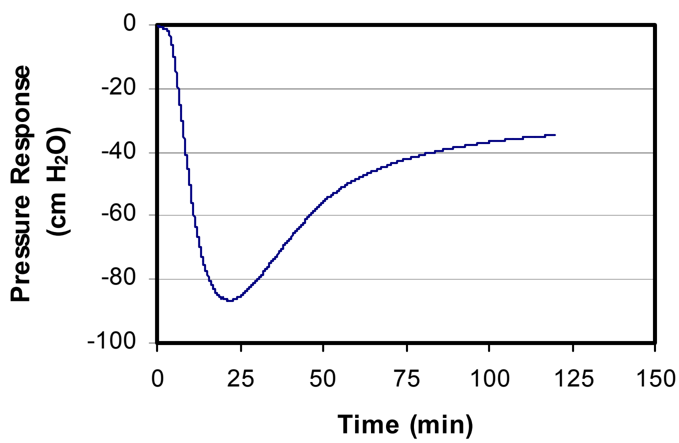




**Figure 5-29. Pressure Response at Monitoring Well MW12r, Camp Pendleton, CA**

## 5.7 Camp Lejeune, SC

**5.7.1 Site Information** Site LCH-4015 was located behind the current civilian gas station and near previous storage tanks. Groundwater at this site was extremely shallow (3 ft). The system consisted of an air sparging and SVE system. Air sparging is being implemented with a continuous air compressor via 38 wells. SVE is problematic due to shallow groundwater and rain events causing it to function as a water pump. Each wellhead had a small flow meter allowing the flow to be balanced between wells. No additional equipment was installed by the MAS team.

**5.7.2 Results.** Pressure tests were conducted by selecting the ends of "arms" of the sparge network with a monitoring well within a few feet. Monitoring wells MW3, MW4, and MW1 were 2-inch monitoring wells in which the pressure transducers were placed. MW3 is located near the new tank fill pad. MW4 is located near the housing complex. MW1 was near a curve in the road near the post office.

The tests were conducted by placing transducers into the monitoring wells and shutting off the sparge point located nearest the monitoring well. Pressure response curves are shown in Figures 5-30 and 5-31. Pressure response was slow and did not drop to hydrostatic levels during the test period. This would indicate that some air is being trapped within the aquifer. This may have been the result of air being trapped below the water table. It may also have been due to complications resulting from the other wells in the system. In retrospect, a compressor should have been used to inject into an individual well.

**5.7.3 Summary and Conclusions.** The well spacing implemented at this site and the monitoring of air flow at the well head made this one of the best-designed sites visited by the Multi-Site Air Sparging Team. To improve the effectiveness of a well-designed system, the following operational recommendations are made for this site:

- Consider switching the compressor to a pulsed cycle 6 h on/6 h off to potentially increase the effectiveness of the air sparging system. In addition, this would add to the life of the air compressor, due to the difficulty in maintaining a compressor 24 hours a day.

- Plumb wells via a number of banks that could be switched on and off to better accommodate the compressor, changing remediation patterns, and provide ability to vary flowrates at different parts of the site.

- Depending on regulatory constraints, discontinue use of a hard-to-maintain (due to shallow water table) SVE system. If vapor migration poses a concern to nearby substructures or buildings, monitoring could be conducted in those areas to monitor vapor migration, or the SVE system could be modified to target problem areas only.

- Use of solenoids would allow pulsing of banks of wells.

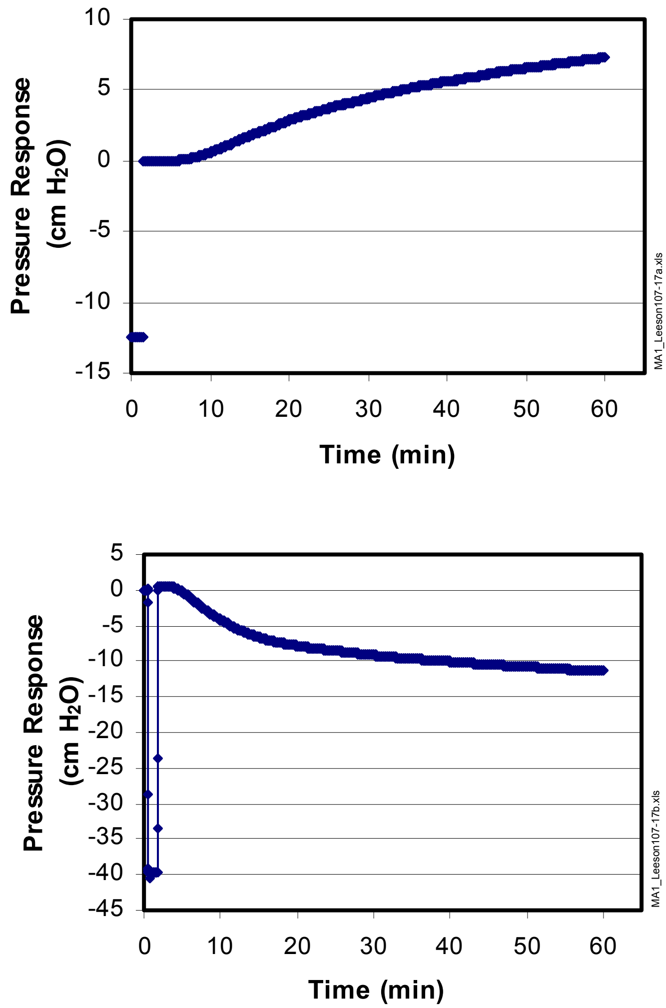
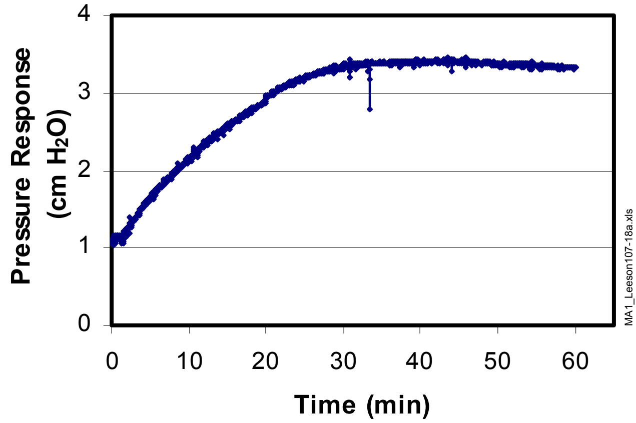



**Figure 5-30. Pressure Response at Monitoring Well MW1, Camp Lejeune, SC**



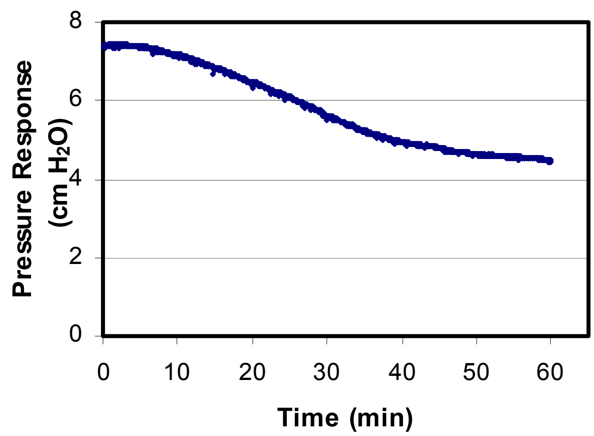




**Figure 5-31. Pressure Response at Monitoring Well MW4, Camp Lejeune, SC**

## 5.8 McClellan AFB, CA

**5.8.1 Site Information.** Only existing installations were utilized at this site. In brief, the site consisted of two test plots, each containing a central injection well and six groundwater monitoring points. One test plot (C) receives propane mixed with the injection air to stimulate propane-degrading microorganisms that can degrade chlorinated contaminants at the site through a cometabolic mechanism. The second test plot (A) is an air sparging only site.

**5.8.2 Results.** Pressure tests and $SF_6$ tracer tests were conducted at both the control (A) and active (C) sites. Because of the elevated levels of helium in the vadose zone, a helium tracer test was not conducted. Air was injected into the active site and the control site injection well at a flowrate of 10 scfm. During active site air injection, water table response was measured in MW-A1

and at the control site, the water table response was monitored in monitoring wells MW-C3 and MW-C4.

The two sites have aspects that are both similar and different. Specific details about the results are provided in the following paragraphs.

Injection pressure for the active site was significantly higher than for the control site (20+ psi versus 10 psi) at a nominal 10 cfm flowrate. Pressure responses in the monitoring wells were similar at both sites. In general terms, the pressure responses were fairly large (>1 m of water in several cases) and the pressure changes persisted for hours. This would suggest that stratification was playing a role in the air distribution at both sites.

At the control site, the water pressure change during startup was approximately 120 cm. The behavior of the pressure after approximately 2.5 hours is unusual in our experience. It suggests that there was some fairly steady increase in the volume of trapped air over the duration of the test (Figure 5-32). The shutdown data would appear to be consistent in that there is an extended period during which the pressure remains below hydrostatic levels.

Data for the active site are similar; however, due to operational constraints, the tests were not run as long as at the control site (Figure 5-33). In addition, system shutdown at the active site was initiated before the system had time to come to equilibrium. (That is the reason the pressure at the beginning of shutdown of the active site is above hydrostatic. In both cases the transducer readings were not adjusted after initial startup). Pressure results at this site also indicate that there may be trapped air, particularly in the vicinity of MW-C3.

$SF_6$ was injected simultaneously into the two sites for a period of approximately 2 hours to examine the distribution of sparge air below the water table. Following that time, the system was shut down and groundwater samples were collected from all of the monitoring wells. Concentrations of $SF_6$ in the groundwater (expressed as percent of saturation with respect to the injection concentration) are shown in Figures 5-34 and 5-35. The distributions for the two sites are significantly different. At the control site, there was essentially no $SF_6$ observed at the 117 ft depth, while at the 113 ft depth significant concentrations were observed at all wells from which samples were collected (i.e., all except well 3). In contrast, at the active site (Figure 5-35), $SF_6$ was observed at both levels in wells 2, 3 and 4, but no $SF_6$ was observed at either level in wells 1, 5, and 6.

Both the $SF_6$ and the pressure data suggest that stratigraphy is impacting the distribution of air at the site. However, results from the $SF_6$ testing indicate that this does not appear to be significantly detrimental to air distribution in the region. At the control site, air does not appear to be contacting the lower depths of the aquifer (117 ft), but appears to be well distributed in the upper region of the aquifer (113 ft). At the active site, there appears to be preferential flow into the western portion of the test plot, with air reaching both the upper and lower portions of the aquifer, but not detected at

A)

B)

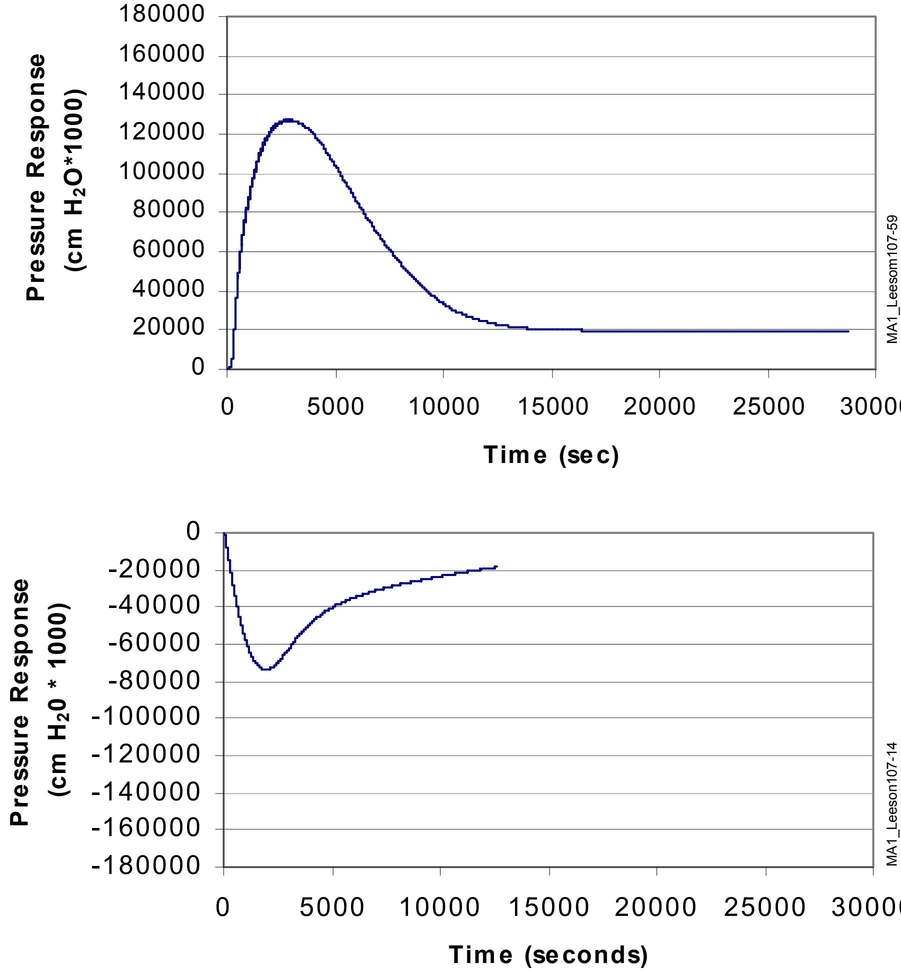
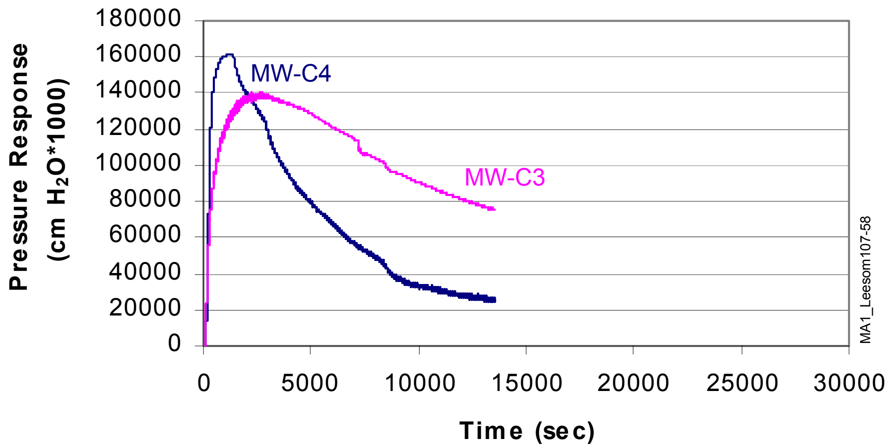



**Figure 5-32. Water Pressure Change at MWA1 during (A) Start-Up and (B) Shutdown at the Control Site, McClellan AFB, CA**



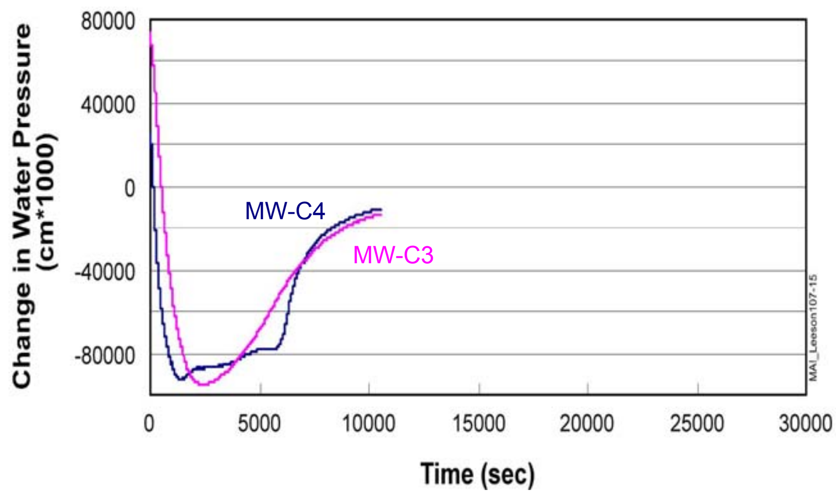




**Figure 5-33. Water Pressure Change at MW-C3 and MW-C4 during Start-Up (A) and Shutdown (B) at the Active Site, McClellan AFB, CA**

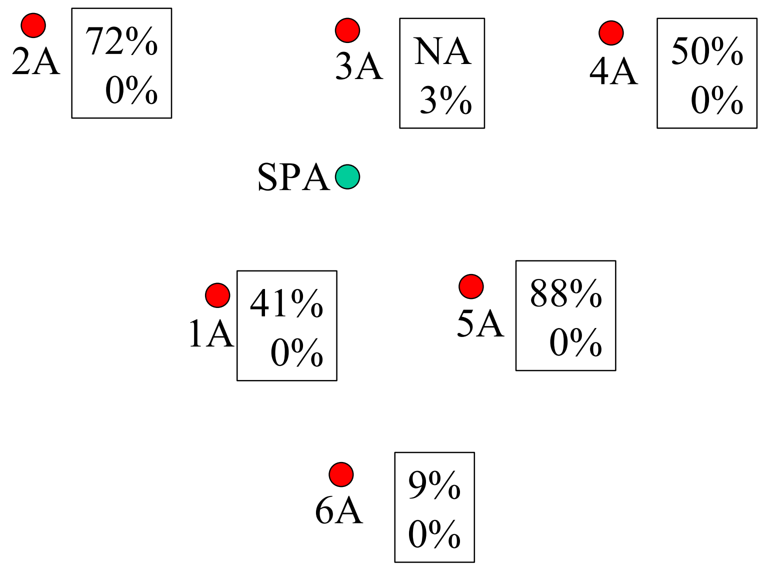



**Figure 5-34. $SF_6$ Data Expresses as Percent Saturation with Respect to the Input Concentration at the Control Site, McClellan AFB, CA**

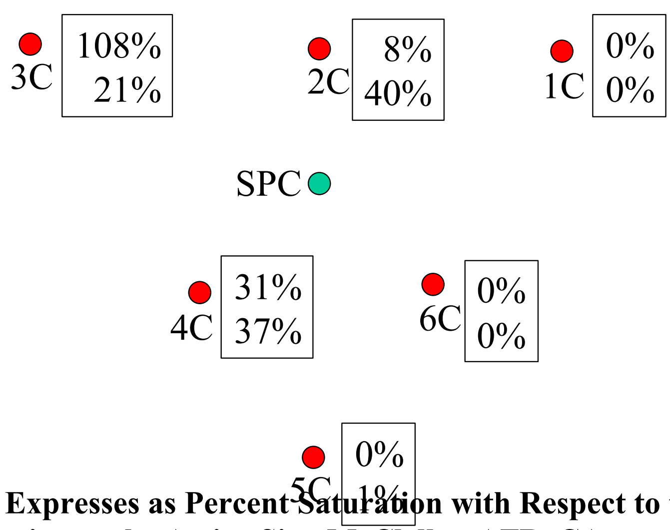



**Figure 5-35. $SF_6$ Data Expresses as Percent Saturation with Respect to the Input Concentration at the Active Site, McClellan AFB, CA**

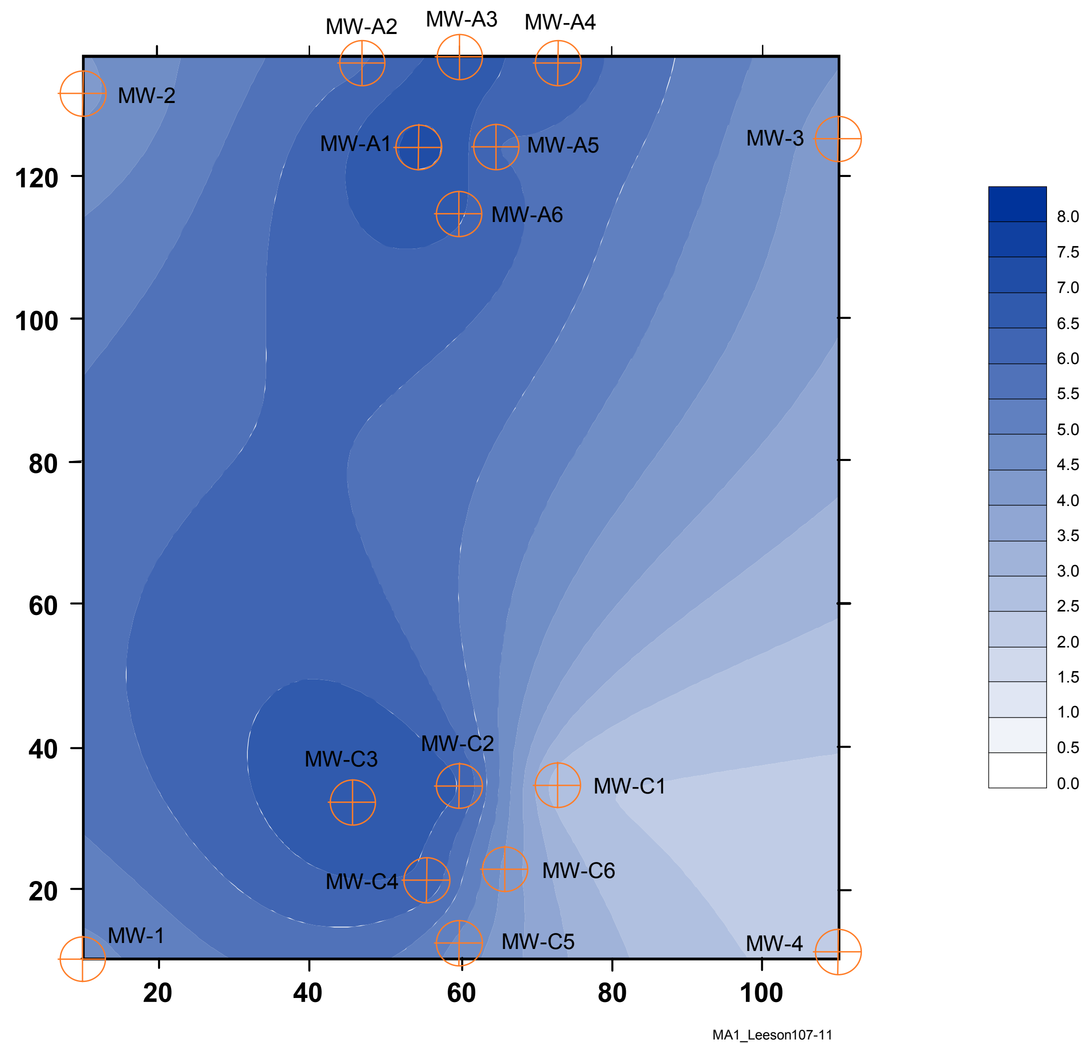



**Figure 5.36 Oxygen Distribution at the Active Test Plot After Air Injection, McClellan AFB, CA**

any depth in the eastern portion of the aquifer. Measurements of dissolved oxygen conducted previously confirm this observation, with higher dissolved oxygen levels achieved in the western quadrant (Figure 5-36).

**5.8.3 Summary and Conclusions.** The results from the two systems demonstrate that differences in stratigraphy that can be seen within a fairly small region. However, the heterogeneous air distribution observed at the active test plot does not preclude implementing air sparging. Well spacings based on the Air Sparging Design Paradigm would likely improve this air distribution in a

full-scale installation. For this site, it is anticipated that 15-ft spacings would be sufficient to ensure good sparge air coverage. However, the depth of the site may be prohibitive.

Pressure tests, $SF_6$ testing, and dissolved oxygen measurements confirmed that the zone of influence within approximately 15 ft of the injection wells. While $SF_6$ tracer testing was able to confirm and clarify the results obtained with pressure and helium tracer testing, the data also was useful for solidifying the pilot testing portion of the Air Sparging Design Paradigm, where the more simple tests such as pressure and helium tracer testing are recommended.

## 5.9 Hill AFB, UT

**5.9.1 Site Information.** No additional equipment was installed at this site as described in Section 4. In brief, the pilot-scale system consists of a line of four air sparging wells surrounded by a network of nested groundwater and vadose zone monitoring points.

**5.9.2 Results.** Vertical permeability was measured using intact soil cores from the site in a constant-head permeameter. The data are shown in Figure 5-37 and indicate that there is a very high conductivity layer at about 125 ft bgs and that the conductivity decreases by several orders of magnitude in the upper portions of the saturated zone. If the lower-permeability layer is extensive, then this permeability contrast would be sufficient to cause the stratigraphic entrapment of the air inferred from the pressure data.

Groundwater pressure increases in excess of 300 cm were observed at the wells closest to the injection well. Pressure increases of nearly 200 cm were observed even at a distance of 130 ft (Figure 5-38). The pressures remained elevated for nearly two days, until the sparging system was turned off. This is indicative of an extensive layer that is effective at preventing upward migration of the air and is consistent with the helium tracer data for the site (Johnson et al., 2001b).

Under normal operation, the total air sparging injection rate for the four wells was approximately 50 scfm and the extraction rate from the eight SVE wells was about 175 scfm. A tracer recovery test was conducted at the site under steady sparging conditions by injecting helium into the air sparging wells at a total rate of 0.55 scfm. The concentration in the air coming from the SVE system was measured as a function of time and after approximately 500 minutes of injection, a helium recovery rate of approximately 20% was measured (Figure 5-39).

During the test it was observed that air was flowing from a number of the shallow monitoring wells that were screened 5 to 10 ft below the water table. As a consequence, the air flow and helium concentrations from each of the wells were monitored during the test. In Figure 5-40 the upper number associated with each monitoring well is the total flow of air out of the well, the lower number is the flowrate of helium out of the well (i.e., helium concentration times total flowrate). The total helium flowrate into the system is 0.55 scfm. As can be seen, approximately 75% of the

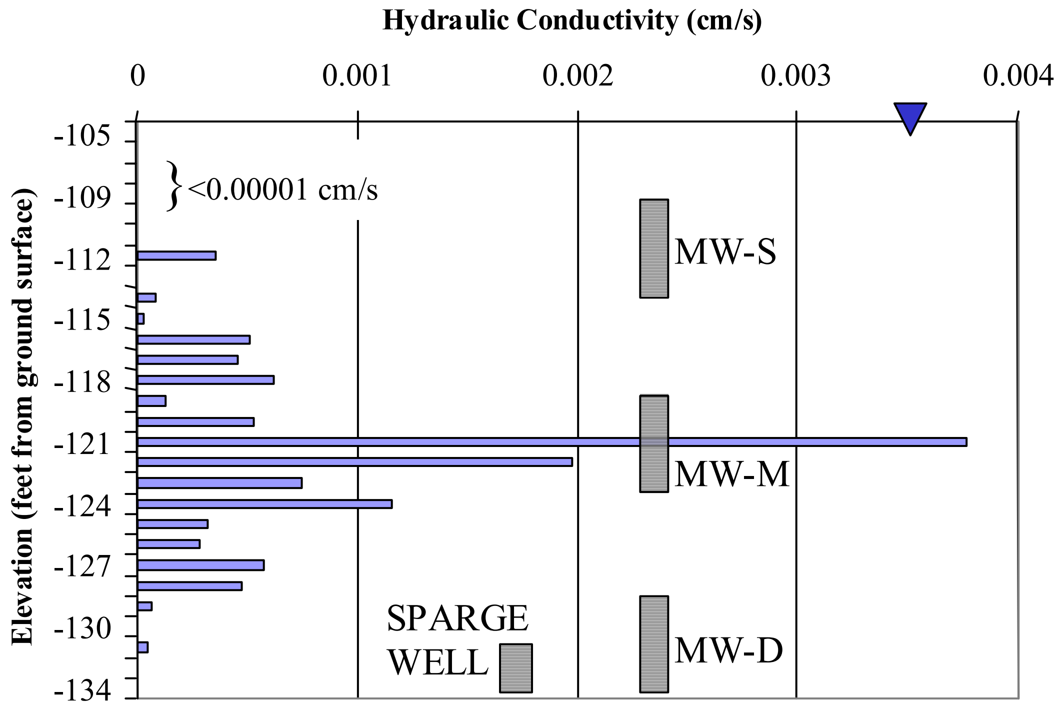



**Figure 5-37. Hydraulic Conductivity versus Depth, Hill AFB, UT**

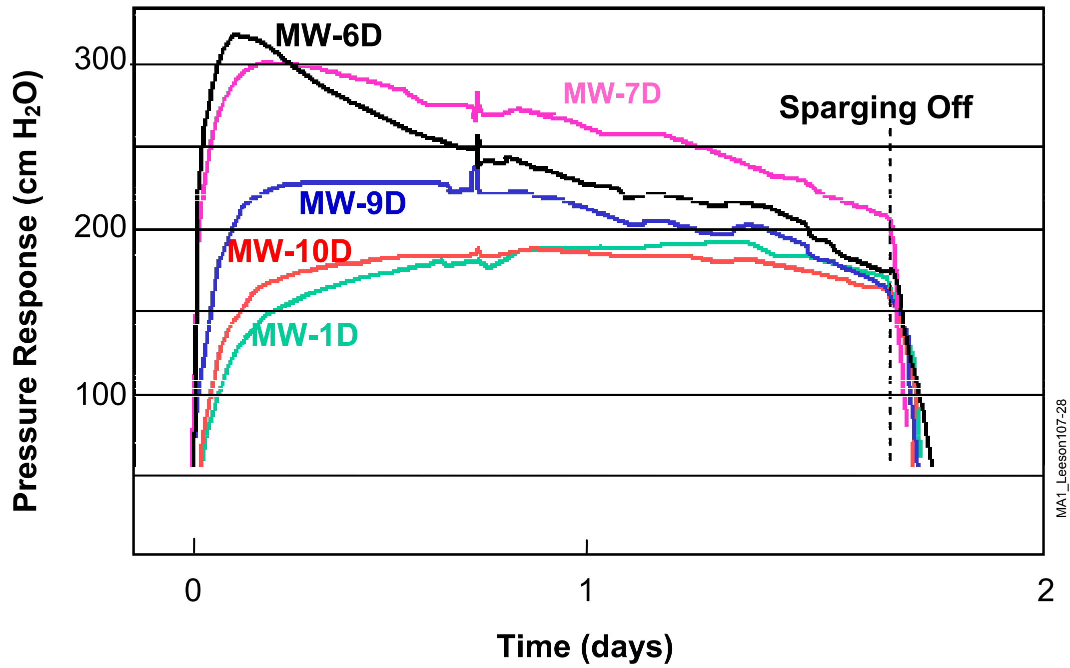



**Figure 5-38. Pressure Response at Monitoring Wells, Hill AFB, UT**

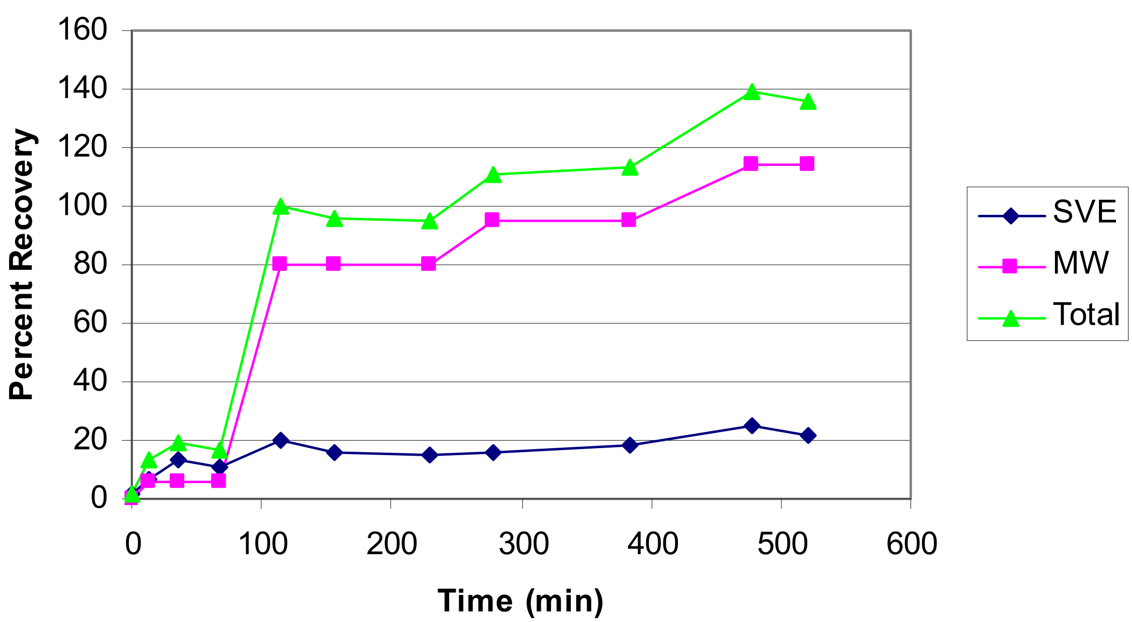



**Figure 5-39. Helium Recovery in SVE Off-Gas, Hill AFB, UT**

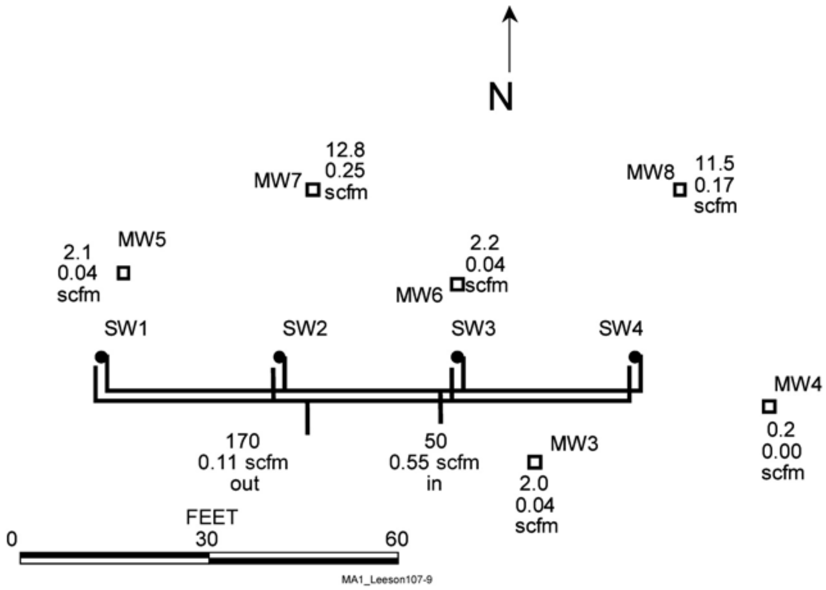



**Figure 5-40. Air Flow and Helium Concentrations at Monitoring Points, Hill AFB, UT**

injected helium was flowing out of monitoring wells 7 and 8 and only approximately 20% of the helium is being captured by the SVE system. From the data in Figures 5-39 and 5-40, it can be concluded that air is being trapped in an extensive pocket beneath the water table in the vicinity of the well screens for the shallow wells. This conclusion is supported by the pressure data.

**5.9.3 Summary and Conclusions.** At this site, the bulk of the contaminated groundwater lay below the confining layer so the sparge air was able to be reasonably effective at removing contaminants. However, the system was not capable of lowering concentrations to the drinking water limit (5 µg/L for TCE in this case). Furthermore, there is some concern that the large volume of air trapped below the water table may have had a significant impact on the water permeability of the aquifer and could have caused part of the plume to be diverted around the treatment zone. Therefore, the site operators concluded that pump and treat would be a more effective treatment alternative at this site.

# 6. Cost Assessment

The costs presented in this section have been estimated using RACER 2000, version 2.0.0. In some instances, RACER does not provide costs for procedures recommended by the Air Sparging Design Paradigm (Leeson et al., 2002). In those cases, contractor quotes have been used to estimate equipment. Specific cost items in Table 6-1 and Tables 6-3 through 6-6 are designated with footnotes as to the cost basis used.

## 6.1 Cost Performance

There are many different configurations and sizes possible for an air sparging installation. Perhaps the most common installation is the remediation of source zones at gasoline stations. Therefore, in this section, costs have been estimated based on an air sparging system installed at a gasoline station source zone. Cost assumptions are based on a site area of approximately 5,000 $ft^2$ (460 $m^2$) with a depth to groundwater of 18 ft bgs (4.6 m) and contamination extending to 24 ft bgs (6.1 m). The soil type is assumed to be relatively permeable so that severe air channeling is not a concern. Costs for the air sparging installation described are shown in Table 6-1. It is estimated that the system will run for two years. Outyear costs are discounted as described in the Cost and Performance Report. The total cost for installation and operation of this air sparging system for two years is \$268,250, with a unit cost of \$141 $yd^3$ (185 $m^3$).

## 6.2 Cost Comparisons to Conventional and Other Technologies

Air sparging has become the most practiced engineered in situ remediation option when targeting the treatment of hydrocarbon-impacted aquifers. The most common installation is for remediation of petroleum hydrocarbon source zones. Therefore, this section examines costs associated with remediation of a petroleum hydrocarbon source zone. As mentioned, air sparging would likely be the first remedial alternative considered. However, practitioners have also implemented removal of the contaminated soil and groundwater with installation of sheet piling to prevent further plume development as a more rapid remedial alternative than air sparging.

The cost for soil and groundwater removal with sheet piling installation is shown in Table 6-2. The total project cost for this remedial alternative is \$900,266 with a unit cost of \$474/$yd^3$. Total remediation time is estimated at approximately 10 weeks.

## Table 6-1. Implementation Costs for an Air Sparging System

| Cost Category | Sub Category | Costs ($) |
|---|---|---|
| | FIXED COSTS | |
| 1. CAPITAL COSTS | Site characterization activities[1] | $55,000 |
| | Pilot testing[2]<br>• Equipment and materials<br>• Labor and miscellaneous costs | <br>$13,200<br>$10,200 |
| | Data evaluation, engineering design, Design Plan, procurement of subcontractors, interactions with regulators[3] | $16,700 |
| | Utility clearance; arrangements for equipment/media storage & debris disposal[3] | $4,200 |
| | Full-scale air sparging equipment cost<br>- Air compressor[3]<br>- Installation of 27 air injection points[4]<br>- Flow meters, pressure gauges, piping, & miscellaneous equipment[4] | <br>$11,100<br>$12,100<br>$7,000 |
| | SVE equipment and operation cost[5] | $76,550 |
| | Start-up and Testing[3] | $2,700 |
| | | Sub-Total $208,750 |
| | VARIABLE COSTS | |
| 2. OPERATION AND MAINTENANCE | Weekly maintenance check for one year[3] | $2,800 |
| | Annual utility cost[6] | $22,800 |
| | Quarterly sampling for one year[3] | $4,600 |
| | | Sub-Total Year 1: $30,200 |
| | | Sub-Total Year 2: $29,300 |
| | | |
| | | TOTAL TECHNOLOGY COST $268,250 |
| | | Quantity Treated[7]: 1,900 $yd^3$ |
| | | **Unit Cost ($): $141/$yd^3$** |

[1]Costs estimated using RACER 2000. Includes costs for evaluation of site geology/hydrogeology, site soils/surface hydrology, nature and extent of contamination, and generation of a Remedial Investigation report.
[2]Costs estimated based on contractor quotes. Costs are based on conducting a pilot test using the Standard Design Approach described in the Air Sparging Design Paradigm. Assumes that equipment installation and testing are completed in two weeks, and that helium and pressure monitoring equipment are rented.
[3]Cost estimated using RACER 2000.
[4]Cost estimated based on contractor quote.
[5]Cost estimated using RACER 2000. Assumes a 6-month operation time.
[6]Assumes a 93% efficiency for the motor, a 97% run time, and a utility rate of $0.1116/kw-hour (California rates).
7Assumes at contaminated interval of 10 ft with an areal extent of 5,000 $ft^2$.

**Table 6-2. Implementation Costs for Soil Removal with Sheet Piling Installation**

| Cost Category | Sub Category | Costs ($) |
|---|---|---|
| FIXED COSTS | | |
| 1. CAPITAL COSTS | Site characterization activities[1] | $55,000 |
| | Mobilization[2] | $2,760 |
| | Surveying[2] | $2,122 |
| | Tank and soil removal and disposal[2] | $43,284 |
| | Sheet piling installation[2] | $760,000 |
| | Demobilization and final reporting[3] | $32,500 |
| | Sub-Total | $895,666 |
| VARIABLE COSTS | | |
| 2. OPERATION AND MAINTENANCE | Final sampling[3] | $4,600 |
| | | |
| | TOTAL TECHNOLOGY COST | $900,266 |
| | | Quantity Treated: 1,900 $yd^3$ |
| | | **Unit Cost ($): $474/$yd^3$** |

[1]Costs estimated using RACER 2000. Includes costs for evaluation of site geology/hydrogeology, site soils/surface hydrology, nature and extent of contamination, and generation of a Remedial Investigation report.
[2]Costs estimated based on contractor quotes.
[3]Cost estimated using RACER 2000.

In comparison to soil removal with sheet piling installation, air sparging systems offers substantially lower capital costs. However, the total remediation time for operation of an air sparging system is longer than for soil removal and sheet piling installation.

# 7. Regulatory Issues

Air sparging was a relatively well-accepted technology by regulators prior to this demonstration. However, the technology was losing favor due to system failures, primarily evidenced through rebound of contaminant concentrations after system shutdown. The reasons for the system failures generally were related to poor system design and inadequate system monitoring that gave a false impression of the remedial progress. This study has provided well-researched guidelines for evaluating, implementing, and monitoring air sparging systems, which will considerably improve the success rate. These guidelines have been extensively published and presented to the regulatory and consulting community through workshops and presentations. Therefore, this technology is likely to become a standard practice for remediating many petroleum hydrocarbon source zones and chlorinated solvent plumes.

# 8. Technology Implementation

## 8.1 DoD Need

Air sparging is potentially applicable at petroleum-contaminated source zones and plumes, as well as chlorinated solvent-contaminated groundwater plumes. The DoD currently has over 4,000 sites that fit these parameters (Defense Environmental Restoration Program, 1998). The contaminated volume varies tremendously from site to site, but conservatively, if one estimates a site at 3,700 $yd^3$ (100 ft $\times$ 100 ft $\times$ 10 ft contaminated area) (2,800 $m^3$), then the potential area where air sparging could be applied is 14,800,000 $yd^3$ (11,300,000 $m^3$). Reducing costs associated with the remedial technology for these sites would have tremendous impact on total DoD remediation costs.

## 8.2 Transition

The transition plan for this evaluation, design, and monitoring guidance is summarized as follows:

- The DoD now has a well-researched design document for practitioners to refer to when implementing air sparging. Further demonstrations of the technology are not necessary; however, it is important that Base environmental managers be aware of this design guidance and ensure that air sparging is implemented accordingly. To further this purpose, it is important that Base environmental managers are aware that this design guidance exists.

It is recommended that the design guidance be posted to a web site in a downloadable format and base environmental managers be contacted directly to inform them of its availability. Additional information could be disseminated through additional workshops.

- The DoD is in the best position to disseminate the air sparging design information. Partners from industry could assist with the conduct of additional workshops.
- Practitioners from industry were involved in the development of the design guidance developed during this study (see Acknowledgements in the Air Sparging Design Paradigm). The information would be of great use to practitioners in the field.

# 9. Lessons Learned

In a recent survey of air sparging system design and operations at DoD facilities, the authors observed that many air sparging systems were poorly instrumented and monitored. Based on this work and other experience, it is not unreasonable to conclude that a significant fraction of existing air sparging systems are improperly instrumented and monitored. In particular, users should be aware of the following:

- It is critical that the system be properly instrumented so that flow to each individual air injection well can be verified and measured. It is the authors' experience that many systems do not have this level of instrumentation. Quite frequently systems have a single flow measurement for an entire manifold of air injection wells. In those systems, one cannot determine the flow to each well, or even if there is flow to a given well in a multiple well system (unless only one well operates at a given time during normal system operation). It is the authors' experience that, in systems containing injection wells sharing a common manifold, all the air may be flowing to only a few of the manifolded wells. As discussed in P.C. Johnson et al. (2001), it is the combination of variations in screened intervals, variations in soil properties, and the nature of air flow - injection pressure relationships that leads to this common problem. Thus, individual flow meters, pressure gauges, and valves are critical to proper air sparging system operation.

- As illustrated by Johnson et al. (1997), groundwater quality data obtained from conventional monitoring wells can be compromised by air sparging system operation. In such cases, practitioners often observe rapid increases

in dissolved oxygen levels and rapid declines in dissolved contaminant concentrations. Then, after system operation, contaminant concentrations may rebound to near pre-treatment levels; in some cases, this rebound may occur over periods of 1 to 12 months. Thus, one must be cautious when interpreting monitoring well data at air sparging sites. To help minimize the potential for errors, Johnson et al. (1997) suggest: a) long-term (12 months) monitoring following system shut-down, b) use of discrete (narrowly-screened) sampling installations, or c) short-term (12 to 24 h) continuous slow-purging of conventional monitoring wells (or discrete sampling points) with time-series sampling. With respect to the latter, it has been observed that short-term continuous purging eventually yields samples that are more representative of formation conditions than in-well conditions, and that this might replace the need for longer-term groundwater quality monitoring.

During continued air sparging system operation, it is typically observed that volatilization removal rates decline to low (and often non-detect) levels (e.g., see Bruce, 2001). At that point it is difficult to assess real-time system performance via traditional measurements (e.g., groundwater monitoring, SVE off-gas sampling, etc.). In those cases, if real-time assessment is important, users should consider the tracer-based tests utilized by Amerson et al. (2001) and Bruce et al. (2001).

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# Appendix A: Points of Contact

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# Appendix B: Data Archiving and Demonstration Plan(s)

A web site will be made available that will contain all raw data as well as all reports from this project. The web site will be maintained by Battelle Memorial Institute.